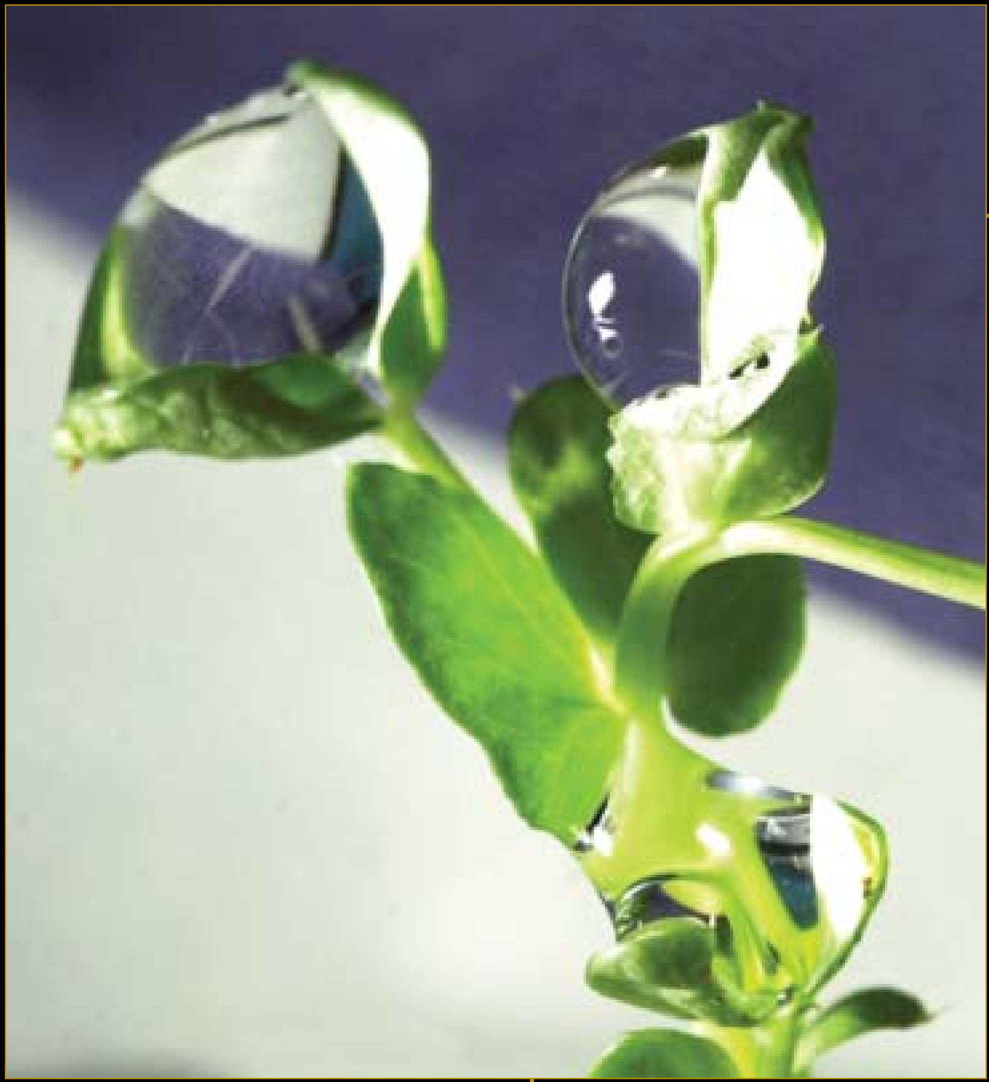
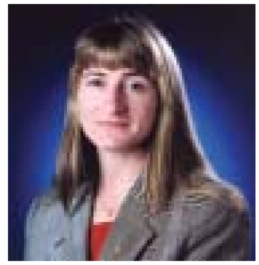


National Aeronautics and Space Administration

Biological and Physical Research Enterprise Strategy

Front cover and above: Held by surface tension, water sits atop a pea plant growing in the International Space Station. Water systems in space must be adapted to microgravity fluid mechanisms. (ISS Expedition Six)

A Message from the Associate Administrator for Biological and Physical Research



October 1, 2003

Dear Colleagues and Friends:

As I reflect on the inspiration that the crew of Space Shuttle Columbia embodies for millions of people around the world, I believe Administrator Sean O'Keefe captured it well when he said, "They gave their lives for something they believed in completely: the peaceful pursuit of discovery." Like the research community they supported, the crew was diverse in background and culture yet united in the pursuit of discovery. Reflecting the best in the human spirit, the crew sought to advance human exploration of space and create new knowledge to help solve problems that face all of us on Earth every day—from pollution to limited energy resources to cancer. As our researchers, administrators, and staff continue with their contributions to the pursuit of discovery, for which these seven dedicated astronauts made the ultimate sacrifice, they capitalize on the resources with which they are entrusted. Toward this end—and in support of NASA's mission "to understand and protect our home planet, to explore the universe and search for life, and to inspire the next generation of explorers"—we within the Biological and Physical Research Enterprise are developing a comprehensive strategy to guide and prioritize all research and other activities throughout the Enterprise. The foundation of the strategy includes our 10-year Enterprise research plan, input from the Enterprise research community and staff, and advisory committee reports. Here are a few highlights from the strategy:

- We focus efforts to answer a clearly articulated set of organizing questions.
- We measure our ability to realize excellence in technical and management performance, research outcomes, and impact.
- We look forward to new suites of missions providing regular opportunities for research.
- We employ and partner with a strong, diverse investigator community.

Five organizing questions are the basis for the Biological and Physical Research Enterprise Strategy: (1) How can we assure the survival of humans traveling far from Earth? (2) How does life respond to gravity and space environments? (3) What new opportunities can research bring to expand understanding of the laws of nature and enrich lives on Earth? (4) What technology must we create to enable the next explorers to go beyond where we have been? (5) How can we educate and inspire the next generation to take the journey? The answers to these questions determine our research strategy, the platforms or programs to execute the science, applications for the research, and the metrics to measure progress. As we fulfill our Enterprise strategy, we contribute in an integral way to realizing the NASA Vision: to improve life here, to extend life to there, and to find life beyond. In doing so, the Enterprise helps not only our scientific, educational, and industrial partners, but also citizens around the globe.

Mary E. Kicza

Mary E. Kicza
Associate Administrator for Biological and Physical Research

Acknowledgments

The NASA Biological and Physical Research Enterprise would like to express appreciation for the work undertaken by the members of our science community to help formulate this Enterprise Strategy.

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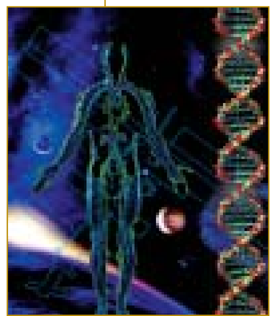
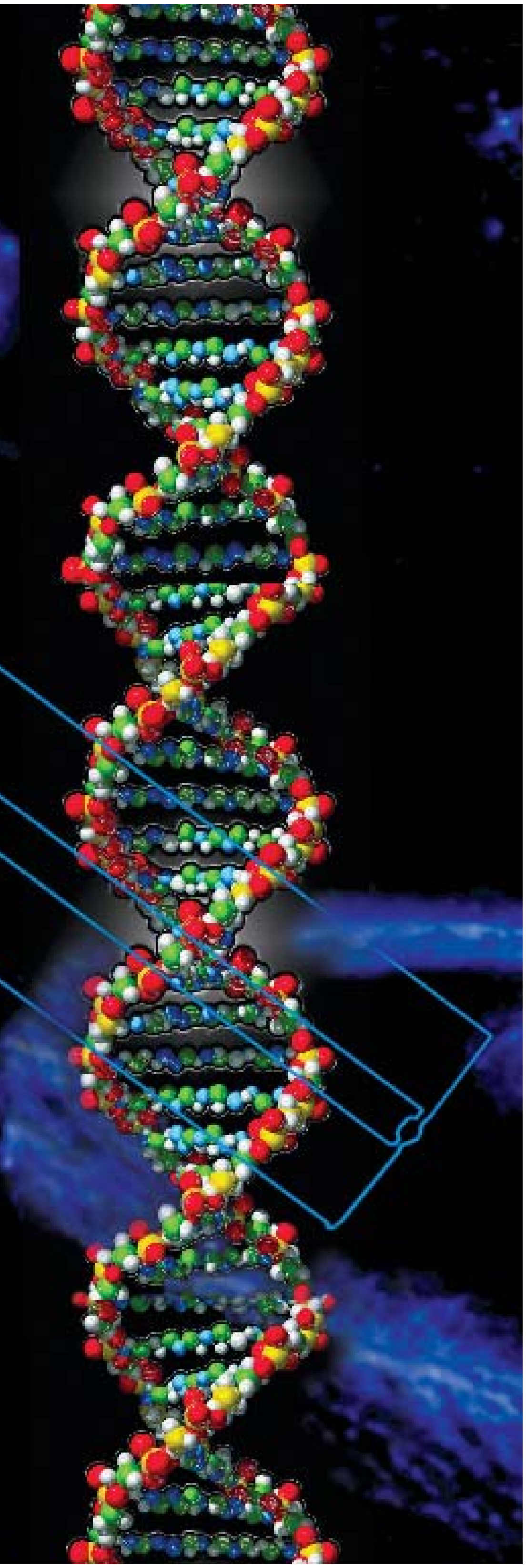


1 Biological and Physical Research and NASA's Vision and Mission



1 Biological and Physical Research and NASA's Vision and Mission

As the 21st century begins, NASA's new Vision and Mission focuses the Agency's Enterprises toward exploration and discovery. The NASA Vision is as compelling as it is succinct:

To improve life here,

To extend life to there,

To find life beyond.

The NASA Mission guides the Enterprises toward achieving the Vision by calling us to

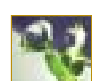
Understand and protect our home planet,

Explore the universe and search for life,

Inspire the next generation of explorers

. . . as only NASA can.

The Biological and Physical Research Enterprise has a unique and enabling role in support of the Agency's Vision and Mission. Our strategic research seeks innovations and solutions to enable the extension of life into deep space safely and productively. Our fundamental research, as well as our research partnerships with industry and other agencies, allow new knowledge and technologies to bring improvements to life on Earth. Our interdisciplinary research in the unique laboratory of microgravity addresses opportunities and challenges on our home planet as well as in space environments. The Enterprise maintains a key role in encouraging and engaging the next generation of explorers from primary school through the graduate level via our direct student participation in space research.



The NASA Strategic Plan establishes seven strategic goals and three enabling goals to execute the Agency's mission. Each of the Enterprises defines its programs according to these goals and focuses management accountability through its designated budget themes. The Biological and Physical Research Enterprise has primary and supporting responsibility for particular goals as indicated in table 1.1.

As depicted in table 1.1, the Biological and Physical Research Enterprise encompasses three themes. The biological sciences research theme investigates ways to support a safe human presence in space. This theme addresses the definition and control of physiological and psychological risks from the space environment, including radiation, reduced gravity, and isolation. The biological sciences research theme is also responsible for the development of human support systems technology as well as fundamental biological research spanning topics from genomics to ecologies. The physical sciences research theme supports research that takes advantage of the space environment to expand our understanding of the fundamental laws of nature. This theme also supports applied physical sciences research to improve safety and performance of humans in space. The research partnerships and flight support theme establishes policies and allocates space resources to encourage and develop entrepreneurial partners' access to space research.

Table 1.1

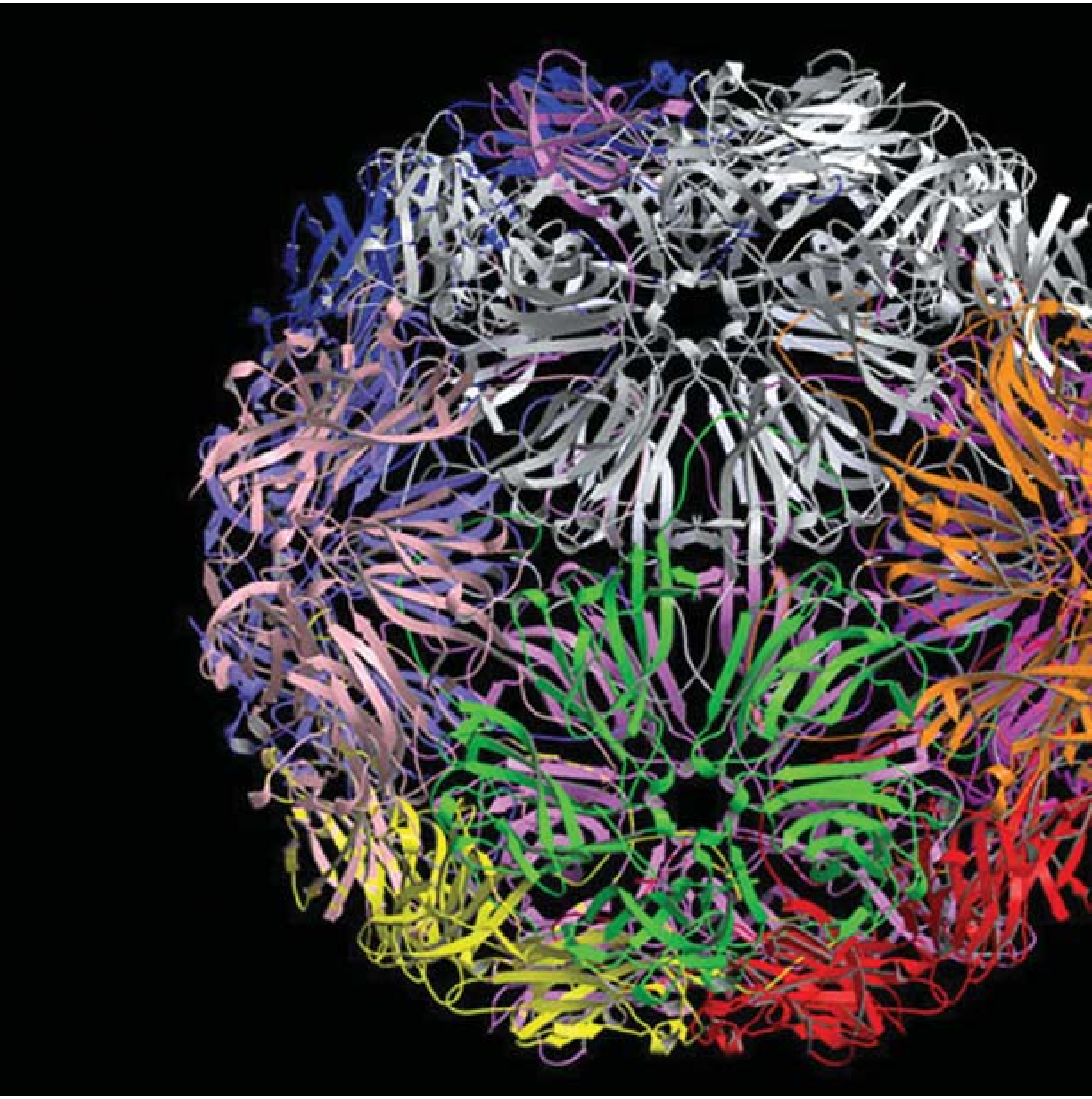
Biological and Physical Research Enterprise Contributions to NASA Goals

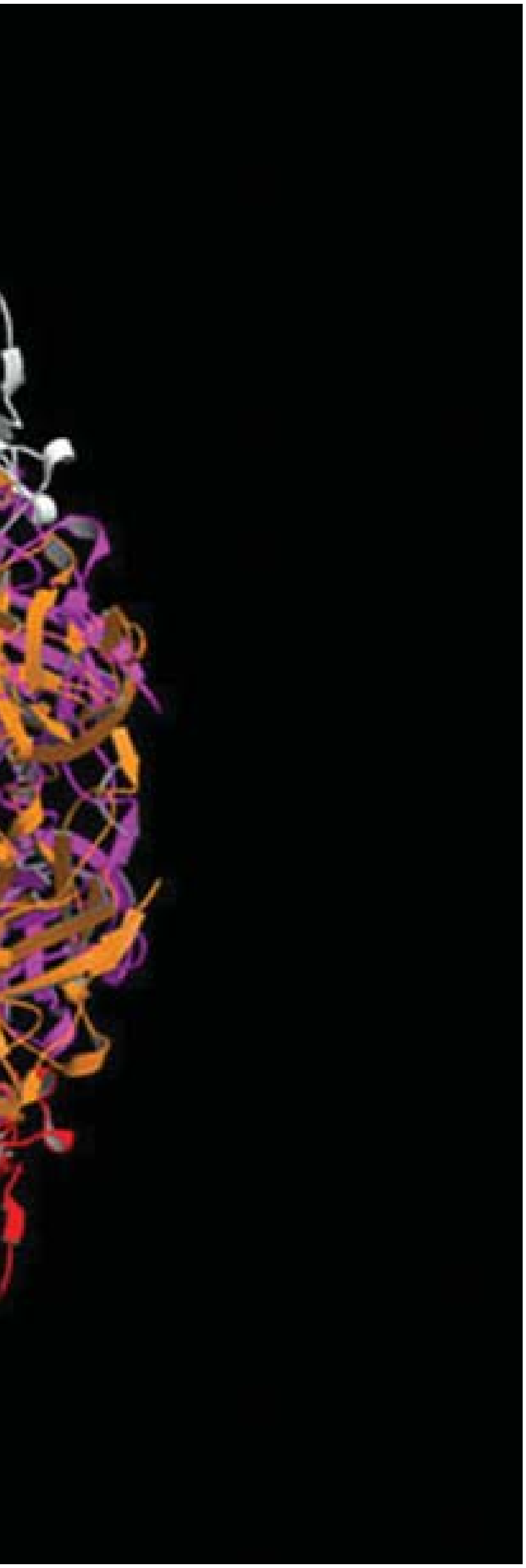
		NASA Budget Themes		
NASA Mission Elements	**NASA Strategic Goals**	**Biological Sciences Research**	**Physical Sciences Research**	**Research Partnerships and Flight Support**
Understand and protect our home planet	1. Understand Earth's system and apply Earth system science to improve the prediction of climate, weather, and natural hazards.			
	2. Enable a safer and more secure, efficient, and environmentally friendly air transportation system.			
	3. Create a more secure world and improve the quality of life by investing in technology and collaborating with other agencies, industry, and academic institutions.		●	●
Explore the universe and search for life	4. Explore the fundamental principles of physics, chemistry, and biology through research in the unique natural laboratory of space.	●	●	
	5. Explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.			
Inspire the next generation of explorers	6. Inspire and motivate students to pursue careers in science, technology, engineering, and mathematics.	◯	◯	◯
	7. Engage the public in shaping and sharing the experience of exploration and discovery.	◯	◯	◯
NASA Enabling Goals				
	8. Ensure the provision of space access and improve it by increasing safety, reliability, and affordability.			
	9. Extend the duration and boundaries of human space flight to create new opportunities for exploration and discovery.	●	●	
	10. Enable revolutionary capabilities through new technology.			

● Primary Contribution ◯ Supporting Contribution

2

Role of the Biological and Physical Research Enterprise



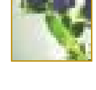


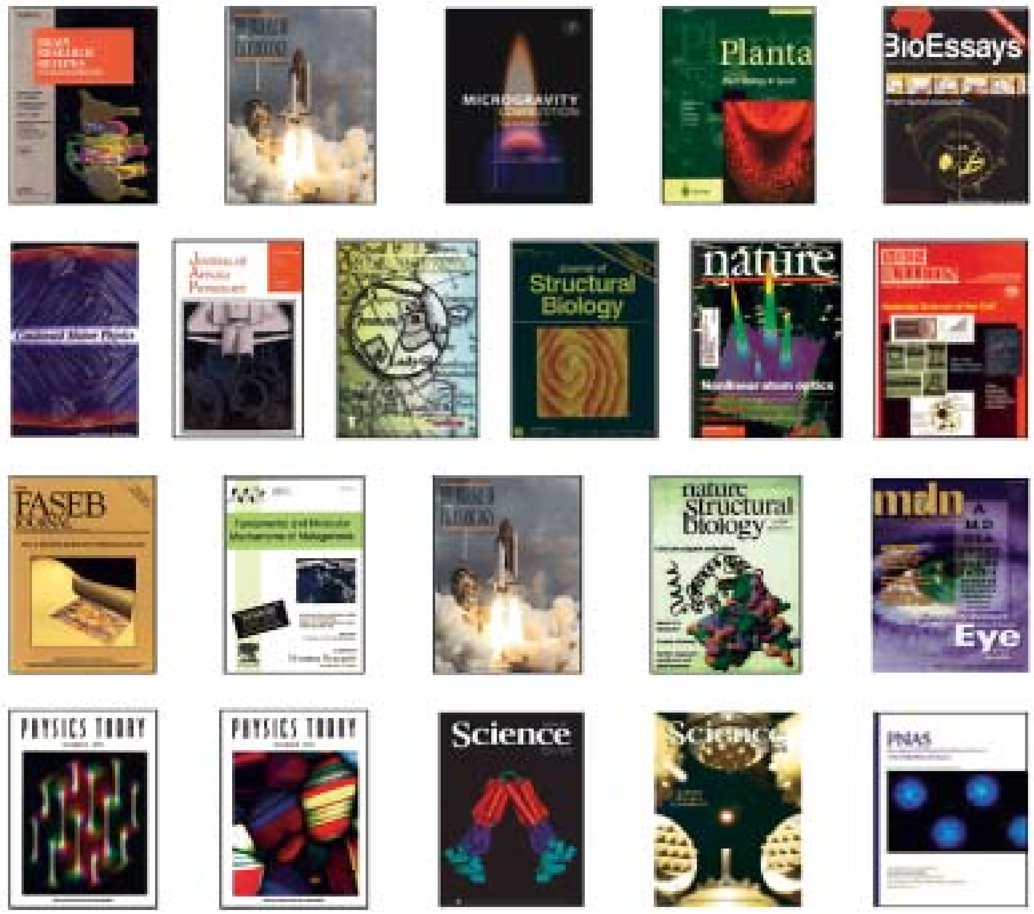
2 Role of the Biological and Physical Research Enterprise

For over 40 years, NASA has sent people on short forays in orbit around the home planet to conduct scientific and engineering experiments in the world of microgravity. Researchers sought to understand gravity in the physical universe and its impact on life itself. They learned that the effects of gravity on Earth limit knowledge of biology, physics, and chemistry. Another discovery was that biological systems—from cells to plants to humans—undergo changes during long-term space exposure that are not yet completely understood. Thus, building on the legacy of Apollo, humankind's eventual travel beyond Earth's orbit into new environments requires a comprehensive program of research to prepare explorers to withstand hazards encountered in space environments. The Enterprise researchers seek to discover new knowledge, technology, and innovations to enable scientific exploration and bring benefits to people on Earth.

The Biological and Physical Research Enterprise has a successful history of research in life and microgravity sciences. Flagship missions flew successfully on the Space Shuttle and Mir, in anticipation of the construction of the International Space Station (ISS). These investigations, which evolved into the Enterprise research portfolio of today, have nearly doubled in the last 6 years—from fewer than 350 to greater than 1,000 research investigations. Published journal articles and patented technologies reflect this growth. In 2002, our 803 principal investigators produced 4,072 research publications. The investigators' credentials are broad and deep, ranging from winners of

The structure of the Satellite Tobacco Mosaic Virus—one of the smallest viruses known—was successfully deduced using crystals grown aboard Shuttle flights. The results are scientific evidence of the benefits of microgravity growth conditions.





Research sponsored by the Biological and Physical Research Enterprise has appeared on the covers of major scientific journals and books.

the Presidential Early Career Awards for Scientists and Engineers to members of the National Academy of Sciences and National Academy of Engineering to Nobel Prize laureates. Similarly, Research Partnership Centers currently work with 176 commercial U.S. companies, developing 106 product lines. These product lines range from agribusiness to biotechnology to materials science to medical research. Access to the space environment via the ISS allows scientists to conduct unprecedented research in microgravity, opening opportunities to answer long-standing questions on science and technology.

While the past demonstrated the merits of the Biological and Physical Research Enterprise's work and validated the concept of an orbital laboratory, new areas of emphasis carry the Enterprise beyond fundamental scientific studies into coordinated strategic research thrusts. Strategic research addresses topics such as radiation health and protection, biomedical research, and engineering research supporting the technologies required for sustained human exploration of space. For humans to venture into space, beyond where we have been, NASA must be able to provide the same kind of safe cocoon for space explorers that Earth provides for its inhabitants. Understanding the challenge of adaptation of humans and other life forms to the effects of space flight is a critical role for the Biological and Physical Research Enterprise.

The Enterprise contributes to realizing the Agency's vision through five organizing questions. These questions provide a framework for all Enterprise activities on the ISS.

1. How can we assure the survival of humans traveling far from Earth?

2. How does life respond to gravity and space environments?

3. What new opportunities can research bring to expand understanding of the laws of nature and enrich lives on Earth?

4. What technology must we create to enable the next explorers to go beyond where we have been?

5. How can we educate and inspire the next generation to take the journey?

This Strategy offers a top-level discussion of the Enterprise approach to answer these questions. The answers do not come easily. A systematic approach, applying a combination of national, international, and commercial resources—both on Earth and in space—and stable investments are required. This set of organizing questions engenders more detailed questions, as delineated in table 2.1.

Working together across research disciplines, the Biological and Physical Research Enterprise is performing vital research and technology development to extend the reach of human space flight. The many investigations supported by this Enterprise in the pursuit of answering these questions are unique to the NASA Mission and distinguish NASA's research from that of other agencies.

The Critical Viscosity of Xenon experiment on STS-107 used a sample of Xenon, forcing the element toward its critical point, to induce shear thinning (an important property of polymer-based industrial materials).

Astronaut Peggy Whitson, the first ISS Science Officer, works on the Zeolite Crystal Growth materials process experiment during Expedition 5 on the ISS. Zeolites are frequently used in the petroleum refining industry.

Table 2.1

Biological and Physical Research Organizing Questions

1. How can we assure the survival of humans traveling far from Earth? (Supports strategic goal #9)

- How does the human body adapt to space flight and what are the most effective and efficient ways to counteract those adaptive affects when hazardous?
- How can we limit the risk of harmful health effects associated with exposure of human space explorers to the space radiation environments?
- How can we provide an optimal environment to support the behavioral health and human performance of the crew before, during, and after space flight?
- How can we enable autonomous medical care in space?

2. How does life respond to gravity and space environments? (Supports strategic goal #4)

- How do space environments affect life at molecular and cellular levels?
- How do space environments affect organisms throughout their lives?
- How do space environments influence interactions between organisms?
- Can life be sustained and thrive in space across generations?

3. What new opportunities can research bring to expand understanding of the laws of nature and enrich lives on Earth? (Supports strategic goals #3 and #4)

- How do space environments change physical, chemical, and biophysical processes, the essential building blocks of many critical technologies?
- How do structure and complexity arise in nature?
- Where can our research advance our knowledge of the fundamental laws governing time and matter?
- What biophysical mechanisms control the cellular and physiological behavior observed in the space environment?
- How can research partnerships—both market-driven and interagency—support national goals, such as contributing to economic growth and sustaining human capital in science and technology?

4. What technology must we create to enable the next explorers to go beyond where we have been? (Supports strategic goals #3 and #9)

- How can we enable the next generation of autonomous, reliable spacecraft human support subsystems?
- What new reduced-gravity engineering systems and advanced materials are required to enable efficient and safe deep-space travel?
- How can we enable optimum human performance and productivity during extended isolation from Earth?
- What automated sensing and control systems must we create to ensure that the crew is living in a safe and healthy environment?

5. How can we educate and inspire the next generation to take the journey? (Supports strategic goals #6 and #7)

3 Achieving Biological and Physical Research Objectives


NASA

3 Achieving Biological and Physical Research Objectives

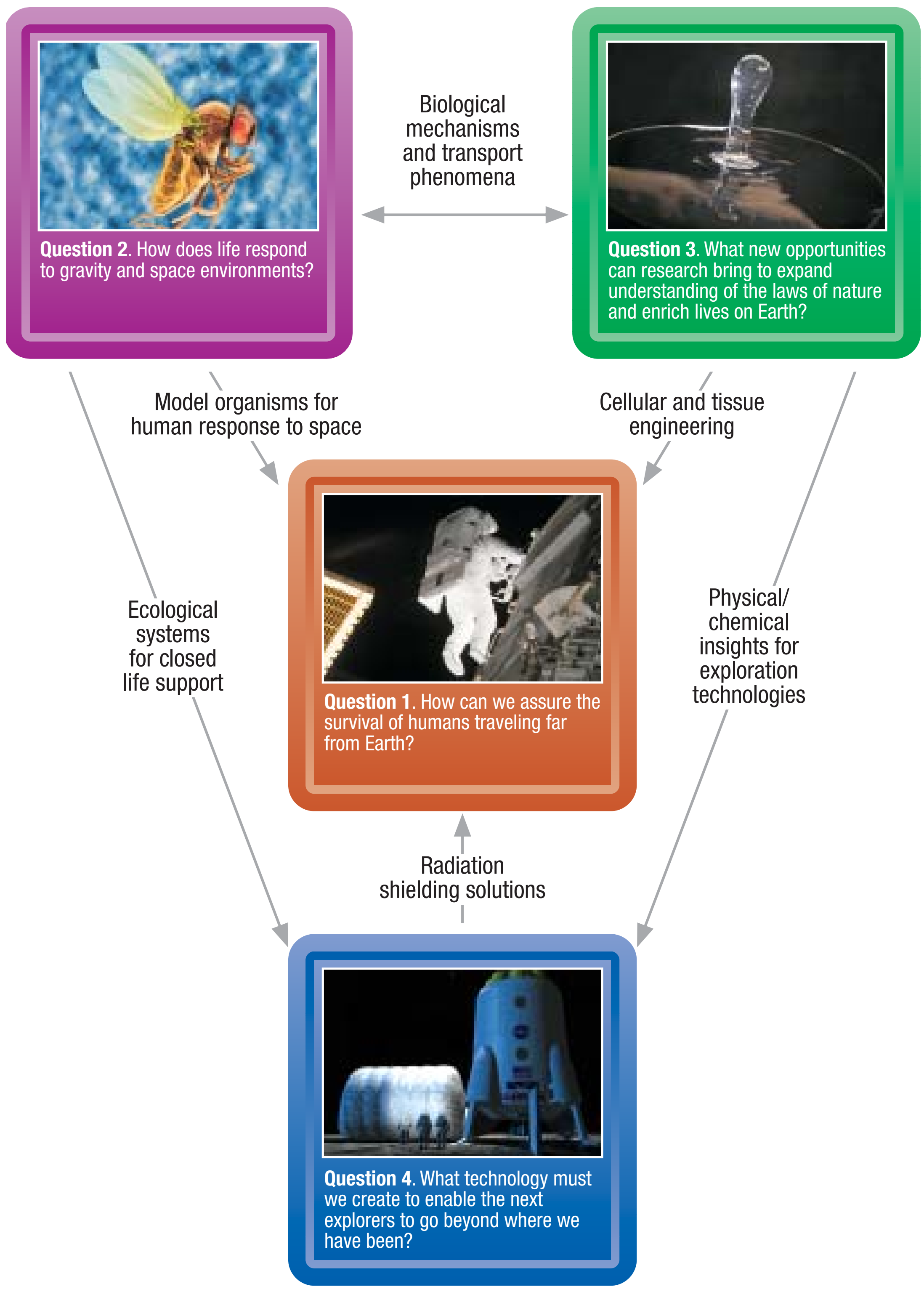
To address the unique challenges presented by research in space, the Biological and Physical Research Enterprise creates cross-disciplinary research programs, bringing the basic sciences of physics, biology, and chemistry together with a wide range of engineering disciplines. The synergy and vigor achieved in this interdisciplinary enterprise will help the Agency meet its long-term goals and ensure that NASA's contribution to fundamental research is at the leading edge of science.

The interdisciplinary nature of our research is expressed in each organizing question. Answering these questions will require an interplay of knowledge and research from multiple disciplines. In addition, the four primary research questions contribute to each other. Figure 3.1 graphically depicts the exchange between the organizing questions. For example, advances in life-support systems closure, a question 4 topic, may rely on the ecological systems and plant research conducted under the auspices of question 2. Note that all questions contribute to question 1—How can we assure the survival of humans traveling far from Earth?—which embodies this Enterprise's unique responsibility to the Agency's Mission "to explore the universe and search for life." These are exemplary (not exclusive) exchanges of the interplay among questions with organizing questions 2 and 3, providing a foundation for exploration countermeasures and technologies addressed in questions 1 and 4.

The Space Radiation Program involves research to help predict and reduce the adverse health effects of radiation on astronauts. Extravehicular activity poses particular challenges to astronaut safety due to limited radiation shielding options.

Figure 3.1

Relationship Between Organizing Questions



Throughout this section each Biological and Physical Research Enterprise organizing question will be explored. More detailed questions are addressed in terms of research challenges, research targets, and enabling technologies. Two timeframes emerge in our research roadmaps and associated research targets. The first timeframe reflects what accomplishments can be expected within our current budget, which has a 5-year horizon. The second timeframe extends to the middle of the next decade, when the Agency will look toward venturing beyond low-Earth orbit. Using the prime capabilities of the International Space Station (ISS), the Biological and Physical Research Enterprise is committed to answering the critical questions to further enable human exploration and the pursuit of basic knowledge for life on Earth. The 2009 to 2016 timeframe also projects the possibility of future strategic programs such as a free-flying spacecraft program to enable additional research opportunities.

Hyperspectral imaging, originally applied to remote sensing, is used to detect damaged skin, as in this image of a burned forearm. This technology also allows for noninvasive analysis of human skin to characterize wounds and wound healing rates, especially important for long-duration space travelers who heal more slowly.

"Medical advances may seem like wizardry. But pull back the curtain, and sitting at the lever is a high-energy physicist, a combinational chemist, or an engineer."

—Harold Varmus
Former Director of NIH and Nobel Laureate

Interdisciplinary Research in the Biological and Physical Research Enterprise

Cutting-edge research crosses the boundaries of traditional disciplines. The Biological and Physical Research Enterprise facilitates cross-fertilization by forming science working groups and providing research opportunities that span its research divisions. This integration maximizes the research contribution to space exploration by providing technological advances in life support and health care and promoting outstanding science. Radiation research is an excellent example of the Enterprise's cross-cutting, integrated approach.

Understanding and mitigating risks from space flight radiation requires scientific investigations in fundamental biological, physical, and materials sciences, as well as applied biomedical research. The Space Radiation Health Science Management Plan provides a framework for collaborative efforts between the Bioastronautics Research, Fundamental Space Biology, and Physical Sciences Divisions of the Enterprise. Specific examples include joint research announcements for ground and flight research and the establishment of NASA Specialized Centers of Research.

Understanding how life functions at the most fundamental cellular and molecular levels requires cross-disciplinary efforts. Knowledge of the mechanisms of cellular response to space environments will provide the first steps in the development of next-generation therapeutics and diagnostics. This knowledge can be applied to countermeasures for space exposure and to improve human health on Earth. Inclusion of genomics within the Enterprise research portfolio will allow use of the significant advances in human, plant, animal, and microbial genetic sequencing and biotechnology. Our Cell Sciences and Genomics Council oversees the following Enterprise areas: establishing research priorities, integrating the research community, coordinating hardware and technology development, and funding joint research announcements.


6

Organizing Question 1.—How can we assure the survival of humans traveling far from Earth?

One of the Agency's primary goals is to extend the duration and boundaries of human space flight and to create opportunities for exploration and discovery. This research strategy provides the foundation and roadmap to assure the health, safety, and performance of crews for missions of varying durations ranging from short-term Shuttle flights to the ISS to advanced exploration missions. Enterprise research ensures that the crew, a critical subsystem of space flight, will not be the limiting factor for human space exploration.

Microgravity sets in motion a range of physiological responses that are not necessarily problematic during space flight but potentially risky upon return to a gravitational environment or during extravehicular activity (EVA). Other hazards are environmental in nature and include exposure of the crew to space radiation and contamination of the spacecraft and its life-support systems. A myriad of psychological stressors associated with living in isolated, confined, and enclosed spacecraft could impair social and physical behavior or performance. Safe tolerance limits and operating bands must be established for the crew during the mission. Establishing safe tolerance limits includes setting mission-specific and lifetime health standards that protect astronauts from any adverse biomedical effects initiated by space flight during and after their flight career. In addition, crewmembers in space can experience many of the medical problems that individuals experience on Earth, including illness and accidents. A healthy and productive crew is essential to maintaining spacecraft (such as the ISS) and performing science experiments in low-Earth orbit (LEO) and beyond.

Our research strategy for assuring human safety, health, and performance is outcome-driven and based on a deliberate interactive approach to reducing the risks of space flight. These include space flights of increasingly greater durations and distances that begin with today's human space flight missions in LEO and evolve to long-duration, interplanetary missions. The approach is based on research targeted to assess, understand, and reduce the probability of risks and the severity of their impact to crew health, safety, and mission success.

This research strategy is based on advisory committee recommendations and National Academy of Sciences reports such as the Institute of Medicine's *Safe Passage* (2001) and the Space Studies Board Committee on Space Biology and Medicine's *A Strategy for Research in Space Biology and Medicine in the New Century* (1998). It derives also from mission-specific crew requirements, as described in the *Bioastronautics Strategy* (2003). The identification, assessment, and mitigation of critical risks associated with the human during space flight have been iterated in the *Bioastronautics Critical Path Roadmap* (*http://criticalpath.jsc.nasa.gov*). To answer the challenge of assuring healthy and safe human space travel far from Earth, four detailed questions must be addressed:

1a. How does the human body adapt to space flight and what are the most effective and efficient ways to counteract those adaptive effects when hazardous?—focuses on understanding, characterizing, and counteracting the whole body's adaptations to microgravity, enabling healthy astronauts to accomplish mission objectives and return to normal life following a mission.

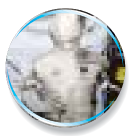
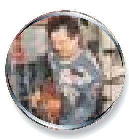
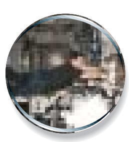
1b. How can we limit the risk of harmful health effects associated with exposure of human space explorers to the space radiation environments?—defines the research strategy necessary to understand the effects of space radiation environments on humans and protect crews from those effects.

1c. How can we provide an optimal environment to support the behavioral health and human performance of the crew before, during, and after space flight?—focuses on the research strategy required to maintain the psychosocial and psychophysiological functions

Astronaut John B. Herrington works on the newly installed Port One (P1) truss of the ISS.

Figure 3.2

Organizing Question 1.—How can we assure the survival of humans traveling far from Earth?

Research Targets		Today	2004–2008	2009–2016
	*Mitigate and manage human adaptation risks*	55 risks identified for outcome-driven research Promising counter-measures identified and studied Knowledge obtained using ground-based mechanistic studies	Characterize and assess critical risks Advance understanding of mechanisms Develop and test candidate countermeasures using ground-based analogs and space flight	Evaluate and validate system-targeted countermeasures to prevent or reduce risks Complete initial in-flight testing of optimized set of countermeasures (artificial gravity with other countermeasures)
	*Reduce uncertainties and prevent exposure to space radiation environments*	Uncertainties exist in estimating radiation risks Study of mechanistic effects in work Exposure mitigated using EVA scheduling and dose limits	Reduce uncertainty by one-half Expand mechanistic understanding using other models Develop and test new countermeasures	Assure at a 95-percent confidence interval crewmembers will not exceed radiation risk limits for longer-duration missions Test and evaluate biomedical and operational countermeasures
	*Maintain behavioral health and optimal functioning of crews*	Psychosocial functioning and behavioral health status studied for individuals Sleep protocols implemented Psychosocial function and performance studied for small groups in remote settings	Identify key psychosocial and psychological stressors Develop and test assessment methods, tools, and models Develop and test optimized countermeasures through ground and space research	Complete identification and increased understanding of psychosocial and behavioral health issues Validate assessment methods and tools Verify and validate countermeasure strategies
	*Develop autonomous medical care capabilities*	Stabilize and return medical care model developed Screening and select-in criteria in place for current mission scenarios	Develop standardized approach to track health status Determine clinical trends and define acceptable levels of risk Perform research to en-hance medical capabilities, including screening, countermeasures, and treatment regimens	Determine acceptable levels of risks for longer-duration missions, and test and validate counter-measures Identify and assess crew screening and certification for longer-duration missions Demonstrate autonomous medical care capabilities
Research Capabilities		**Ground labs including analogs, Shuttle, ISS**	**Ground labs including analogs, Shuttle, ISS**	**Ground labs including analogs and integrated testing, Shuttle, ISS, free flyers**

OUTCOME

Ability of humans to retain function and remain healthy during and after long-duration missions beyond low-Earth orbit

(e.g., sleep and circadian functioning) of the crew for missions of increasing duration and distance.

1d. How can we enable autonomous medical care in space?—addresses the development of medical care systems and tools required to diagnose and treat medical events arising during flight, with an emphasis on increasingly autonomous operations.

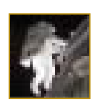
The ISS is essential for determining the long-term effects of space environments and is used as a test bed to assess and characterize risks, to understand the range of physiological and behavioral responses, and to validate an optimal and integrated set of countermeasures and medical operations. The development and initial testing of countermeasures (i.e., active interventions to deleterious changes), medical operations, radiation protection, and crew selection and training procedures occur in ground-based research.

A variety of research models and analog environments (and populations) continue to be used to augment space flight resources. Cellular and tissue engineering research offers a microcosm of more complex forms of life in space environments. Animal models provide insights into mechanisms and processes underlying the physiology and control of adaptive changes. Earth-based analogs of space flight, with their own unique characteristics, play an essential role in the research strategy. Some analogs, such as human bed rest, are integral for countermeasure testing and evaluation. Others, involving isolated and confined settings, such as the Antarctic research station, polar expeditions, and underwater facilities, provide important data relevant to the various physiological, psychological, and behavioral health and performance risks associated with the space flight experience. Mathematical and computer models play a role in understanding mechanisms, integrating research disciplines, and optimizing countermeasure protocols. Such research increases our knowledge base regarding risk assessment and characterization, aids in the development and evaluation of countermeasure protocols, as well as validates medical procedures and tools.

Special research capabilities are required to successfully accomplish the research strategy. Examples include the Human Research Facility on the ISS, human bed rest facilities, altitude chambers, and the NASA Space Radiation Laboratory (NSRL). Ground facilities that house a wide array of centrifuges suitable for human and animal subjects and a slow-rotating room are used to assess artificial gravity effects and potential artificial gravity options for long-duration missions. Hypo- and hyperbaric chambers test more efficient protocols for making EVA safer and research related to understanding, assessing, and mitigating the risk of decompression sickness. Some elements of the research strategy utilize precursor robotic missions and free-flying spacecraft to measure space radiation levels at or near planetary surfaces in order to develop accurate models of the radiation environment, as recommended by the National Research Council (NRC) report, *Safe on Mars* (2002). Other elements such as medical procedures, protocols, and equipment require parabolic flight testing (i.e., aircraft flying reduced gravity trajectories) to evaluate their potential application to microgravity operations.

Partnerships are an integral part of the research strategy and its success. The intramural and extramural science communities (e.g., biomedical, biological, and physical sciences), our international partners, other government agencies, research institutes, and the commercial and specialized research centers participate in the entire research continuum from understanding physiological responses to development and testing of countermeasure solutions and provision of medical care.

The following sections present the research strategy for assuring human health, safety, and performance associated with the questions. Each contains research targets (near- and far-term) and a summary of enabling technologies. Earth applications are summarized after the discussion of the four detailed questions. The integrated roadmap in figure 3.2 illustrates the research targets aligned to specific timeframes and states the long-term research outcome for assuring human survival.



Astronaut Donald R. Pettit, Expedition Six NASA ISS Science Officer, exercises on the Treadmill Vibration Isolation System in the Zvezda Service Module on the ISS.

1a.—How does the human body adapt to space flight and what are the most effective and efficient ways to counteract those adaptive effects when hazardous?

Research Focus: Adaptation and Countermeasures

Microgravity affects virtually every system in the body. The normal processes of adaptation to weightlessness cause bones to lose calcium, muscles to lose strength, nutritional requirements to change, and the immune, cardiovascular, and sensorimotor systems to alter. These changes can result in decrements in crew health, safety, and performance while in reduced-gravity environments and upon return to the one-gravity environment of Earth. The challenges are to enhance our current knowledge of these changes, to understand and characterize the range of physiological responses, and to design and validate countermeasures for maintaining or restoring function to acceptable levels.

Known detrimental changes include bone mineral density losses that vary across specific bone sites with greater loss in the weight-bearing bones. It is not known at what point in time or exposure that the bone loss stops. Marked atrophy of postural muscles as well as reduced muscle strength and endurance may degrade performance of motor tasks and prevent the astronaut from performing sustained work in EVA or emergency egress from the spacecraft. Cardiovascular adaptations to microgravity increase in severity and complexity with flight duration. Postflight orthostatic hypotension (lightheadedness and fainting) when crewmembers stand and egress from the space vehicle is a concern. Other changes in heart function and electrical activity may lead to cardiac dysrhythmias during a mission, particularly during stressful tasks such as EVA. Altered immune function and regulation may increase the risk of infection, allergy, autoimmune disease, and cancer. The potential effects on immune function increase with duration of space flight because of extended exposure to stress with a compromised immune system and possible synergistic effects from radiation exposure. Sensorimotor adaptations occur in stages during flight with spatial disorientation and space motion sickness occurring in early transitions. Adaptation of the balance system and reentry vertigo could be a problem during EVA, teleoperations, and landing, particularly one requiring emergency egress. Reduced caloric intake, weight loss, and other nutritional compromises influence overall health and disease resistance. Astronauts may have unique nutritional needs, such as intake of antioxidants for radiation protection or calcium supplementation for bone loss.

This research strategy develops, evaluates, and validates an integrated countermeasure approach that effectively and efficiently prevents or reduces adverse adaptive changes. To limit bone loss, muscle atrophy, and cardiovascular alterations, active intervention is required that may include pharmacological agents, dietary modification, exercise, mechanical stimulation, artificial gravity devices, or changes in crew screening and selection criteria. The research challenge to alter immune function is to fully assess and understand the extent of the problem and to develop effective countermeasures that minimize the risk to the crew during flight and long-term effects upon return to Earth. Countermeasures to sensorimotor alterations include pharmacological regimes, artificial gravity options, preflight training, and in-flight protocols to counter reentry disturbances and promote rapid return to daily living activities. The Enterprise uses a variety of platforms including ground-based analog environments and relevant populations. The most promising countermeasure strategies developed from the ground-based program are evaluated and validated in space flight. A potential enhancement for the strategy includes studies to test in-flight, artificial gravity options in combination with other countermeasures for long-duration space flight.

Research Targets (2004–2008):

For bone loss:

- Ground- and flight-based research to develop countermeasures to prevent or minimize microgravity-induced acceleration of osteoporosis and bone loss, changes in bone quality, and formation of renal stones

- Develop new predictive strategies and assessment tools for early detection of osteoporosis

- Develop strategies to enhance fracture repair and bone strength, increase resistance and decrease susceptibility to fracture, and understand regional bone growth

For muscle alterations and atrophy:

- Study new countermeasures (both ground- and flight-based) to minimize muscle atrophy, increase muscle strength and endurance using combinations of artificial gravity, aerobic and resistive exercise, and pharmacological therapies

- Undertake studies to better understand the complex relationship between bone and muscle and molecular and cellular processes responsible for muscle metabolism

Astronaut Edward T. Lu, Expedition 7 NASA ISS Science Officer and Flight Engineer, exercises on the Cycle Ergometer with Vibration Isolation System on the ISS.

For cardiovascular alterations:

- Determine whether long-duration exposure to microgravity predisposes individuals to increased cardiac arrhythmias or causes cardiac atrophy, and if so, develop preventative measures

- Continue studies on the mechanisms of orthostatic hypotension and autonomic dysfunction and develop predictive capabilities to individualize countermeasures, integrating cardiovascular countermeasures with bone and muscle countermeasures

For immune function and increased infections:

- Study immune function and determine any increases in numbers or virulence of pathogens

- Develop and test new therapies for maintaining or enhancing immune function

For sensorimotor alterations:

- Develop and test strategies for use during transitions to and from various gravity environments, new preflight and in-flight training techniques, anti-vomiting medications, artificial gravity, predictors of individual susceptibility, and teleoperation interfaces

- Develop new methods for the rapid return to normal activities after flight that enhance postural and locomotor control

For nutrition and performance:

- Determine nutrient requirements and develop strategies to ensure adequate nutrition and provide protocols for using supplemental nutrition

Adequate nutrition is essential to maintain optimal health and performance. Pictured here is a typical Space Shuttle food tray containing packets of dehydrated food and a beverage. Proper nutrition can diminish risks associated with adaptation to microgravity.

- Determine if nutrient intake (such as antioxidants or vitamins) can mitigate health and performance risks associated with adaptation to microgravity

Research Targets (2009–2016):

Evaluate and validate system-targeted countermeasures that accomplish the following:

- Prevent or reduce bone loss (including potential crew screening and select-in criteria), muscle atrophy, and decreases in muscle strength and endurance in long-duration space flight

- Prevent or reduce cardiovascular risks including dysrhythmia, orthostatic intolerance, cardiac atrophy, and cardiac disease

Enabling Technologies: Adaptation and Countermeasures

- Pre- and postflight technologies for systematic and comprehensive data collection
- More precise and accurate on-orbit 3-D imaging devices to measure hip bone density and geometry
- On-orbit bone marker measurement devices
- Resistance training devices that can isolate and integrate different muscle contraction modes
- Orbital artificial gravity options
- Highly sensitive diagnostic vestibular and locomotor testing devices
- Nonencumbering eye-, head-, and limb-motion measurement technology
- Nonsedating anti-motion sickness and other pharmaceuticals with long shelf lives
- Immersive virtual reality technologies without nausea
- Prostheses for balance and movement problems
- Unobtrusive methods to track crew nutrient consumption, metabolism, and health status
- Minimally invasive or noninvasive technology to assay in-flight nutrient utilization
- Measurement devices for gene expression
- Improved food systems
- In-flight cardiac monitoring and diagnostic tools

- Maintain immune function during and after long-duration space flight
- Prevent balance-related impairments associated with gravitational transitions
- Maintain nutritional health during long-duration space flight
- Complete initial testing of an optimized, integrated set of countermeasures
- Evolve countermeasures to flight testing of artificial gravity in combination with resistance training prescriptions and dietary modifications

In this ISS onboard photo, Expedition Six Science Officer Donald R. Pettit works to set up the Pulmonary Function in Flight (PuFF) experiment hardware in the Destiny Laboratory. The PuFF experiment was developed to better understand what effects long-term exposure to microgravity may have on the lungs.

The Phantom Torso is used on the ISS to detect and measure neutron radiation. Having the ISS as a platform on which the physiological effects of such radiation can be studied over time will enable researchers to better develop protective measures.

1b.—How can we limit the risk of harmful health effects associated with exposure of human space explorers to the space radiation environments?

Research Focus: Radiation Health

Space radiation poses risks to crew health and safety during a mission, but unlike some other aspects of space travel, space radiation exposure has clinically relevant implications for the lifetime of the crew as documented by reports from the National Council on Radiation Protection (e.g., 1990, 1997, 2000). Space radiation differs substantially from the radiation environment on Earth, and consists mainly of high-energy protons and atomic nuclei of the heavier elements. The highly charged and energetic nuclei, referred to as HZE particles, are important components of galactic cosmic radiation. HZE particles are less abundant than protons but far more hazardous. Solar disturbances can also contribute to the space radiation environment when they include Solar Particle Events (SPE). High-energy protons are the principal source of radiation in SPE. An additional source of radiation can be found in LEO, where protons are trapped in radiation "belts" at certain altitudes. Protons and HZE particles interact with the material of space habitats, space suits, and the bodies of crewmembers. Consequently, the intensity, energy spectral characteristics, and quality of radiation inside a spacecraft are different from free space, and the radiation dose received by crewmembers varies from organ to organ.

The two most important health and safety risks from exposure to space radiation environments are an increase in the risk of contracting cancer above and beyond the risk of cancer in the general population and damage to the central nervous system. The implementation of radiation protection is based on an advanced understanding of the biological effects from radiation exposure. Techniques to mitigate those risks include operational and scheduling procedures and physical shielding to a level "as low as reasonably achievable." Relatively large safety margins are employed to safeguard crew health, but they may impact crew flight time and pose significant career limits on astronauts.

The research strategy for radiation health protection centers on the fact that space radiation can be well-simulated in ground-based laboratories. Radiation research uses ground-based accelerators at the Brookhaven National Laboratory (BNL), where dedicated beam lines and research support facilities comprise the NSRL. Both HZE particles and protons can be produced at the NSRL to perform focused, mechanistic studies on the biological consequences of exposure to the components of space radiation environments. The basic knowledge obtained from these experiments enables the prediction of health effects attributable to space radiation and will reduce the uncertainties associated with the prediction of known effects, thus reducing the need for large safety margins. The research enables NASA scientists to take full advantage of breakthroughs in biology and develop methods for prevention and intervention to reduce the inevitable risks arising from exposure to space radiation. The results of the research allow crewmembers to participate in three 180-day missions on ISS and long-duration missions beyond LEO, without exceeding risk limits at the 95 percent confidence level.

Research Targets (2004–2008):

- Establish acceptable levels of risk to crew health associated with space radiation exposure
- Continue to reduce the residual uncertainty in measurements of the ISS radiation environment
- Complete ongoing assessment of radiation risk by compiling and analyzing epidemiological data
- Determine potential amplification of radiation risks due to synergistic effects of microgravity on other physiological systems (e.g., immunological changes, sensorimotor alterations, and nutrition)
- Develop an understanding of fundamental biological mechanisms responsible for the health effects of space radiation using animals, cell cultures, and tissue cultures
- Define the space radiation environment as it relates to humans
- Develop and evaluate biomedical countermeasures for space radiation
- Implement an ongoing assessment of radiation risk management status
- Develop and determine implementation strategies for operational countermeasures including shielding, dosimetry, crew selection, nutritional supplements, and pharmacological intervention

Research Targets (2009–2016):

- Reduce risk uncertainties, incorporating biological effects and shielding materials to enable increased mission intervals within acceptable levels of risk
- Determine mechanisms and processes underlying crew risks associated with exposure to the space radiation environment using ground-based facilities

Radiation fields encountered in space may cause deleterious effects in humans. The NSRL beam line at BNL is used to gather experimental data on the effects of exposure of high-energy particles on materials.

- Maintain and refine radiation risk mitigation utilizing new data to predict radiation-related health changes during and after the space flight
- Develop, evaluate, and validate biomedical countermeasures for space radiation risks
- Develop biological and pharmacological countermeasures through leverage breakthroughs in radiobiology
- Test, apply, and validate biological countermeasures for radiation risks

Enabling Technologies: Radiation Health

- Noninvasive technologies to quantify cell and tissue radiation-induced damage
- SPE simulator
- Accelerators and heavy ion microbeams with mixed radiation field capabilities
- Ionizing radiation source (e.g., X-ray machine) for synergistic studies on space-based platforms
- Remote sample handling, processing, detection, and imaging of biological materials

Ensuring the psychosocial and behavioral health of crews during long-duration missions is critical and requires bringing some of the important comforts of home with you. Cosmonaut Sergei Y. Treschev, Expedition Five Flight Engineer, entertains his colleagues on the ISS.

1c.—How can we provide an optimal environment to support the behavioral health and human performance of the crew before, during, and after space flight?

Research Focus: Behavioral Health and Human Performance

The impact of behavioral health and performance on the success of extended-duration missions is associated with psychosocial, circadian, and neurobehavioral adaptation. Psychosocial factors include astronaut selection, crew compatibility, leadership, family support, crewmember and crew-ground interactions, organizational and cultural climate, and post-mission re-adaptation. Sleep and circadian research includes the effects of chronic sleep loss and disruption, the effects of circadian dysregulation, the conditions for maintaining a balanced work/rest schedule, and the physical and social environment. Neurobehavioral research areas include cognition and performance capabilities (e.g., decisionmaking, problem solving, motor skills), and the physiological and psychological responses to stress (e.g., agitation, distress, and psychiatric dysfunction).

Ground-based studies in controlled experimental conditions such as simulations and analog environments/populations incorporate large and diverse (gender and ethnic) numbers of subjects. Animal models, where appropriate, are part of sleep and circadian rhythm studies. These ground studies provide the foundations for space-based research that verifies assumptions and validates ground-based findings. Research yields the optimization of countermeasure strategies to ensure psychosocial adaptation, to prevent circadian rhythm disruption, and to maintain neurobehavioral function. A potential enhancement to the research program is the development of focused studies on small group dynamics, for optimal performance, and on targeted behavioral health and performance countermeasures for individuals and small groups in confined, remote environments.

Research Targets (2004–2008):

- Develop methods to select the most compatible crews and maintain healthy interactions for missions of increasing duration and/or distance
- Identify the key psychosocial, psychological, environmental, cultural factors
- Develop, test, and evaluate methods to select compatible crews and to determine psychological and psychosocial function, including crew-ground interactions
- Develop, test, and evaluate the countermeasure strategies that maintain optimal psychological and psychosocial function and performance and correct inappropriate crew-related interactions
- Maintain circadian function in the space environment for missions of increasing duration
- Use animal models and human studies to test countermeasures to maintain normal circadian rhythms and evaluate new countermeasures for space flight-related sleep loss
- Identify effects of circadian dysregulation and the environmental parameters that ensure optimal crew alertness, sleep, and circadian function for performing mission objectives
- Develop mathematical models to optimize sleep and circadian schedules
- Maintain optimal neurobehavioral function, including performance and psychological health for missions of increasing duration and/or distance
- Identify and understand the key factors in space environments that impair cognitive function and performance, and that increase stress and negatively impact behavioral health
- Develop, test, and validate noninvasive methods of detecting impairments in performance and behavioral health
- Develop, test, and evaluate countermeasures to correct impairments in performance and behavioral health

Research Targets (2009–2016):

- Complete identification of the key psychosocial and psychological factors in missions of increasing duration and/or distance
- Maintain optimal crewmember, crew-ground interactions, and sleep and circadian function in microgravity

The Antarctic is used as an analog to study the long-term effects of isolation on humans. This biomedical research ensures optimal behavioral health and human performance during deep space missions in which crews will experience varying degrees of isolation.

- Continue to maintain optimal neurobehavioral function, including performance, psychological health, and cognitive function

- Validate countermeasure strategies

- Maintain optimal psychological and psychosocial function or correct impairments in performance and behavioral health

- Maintain normal sleep and circadian rhythms or protect from the adverse effects of circadian rhythm changes and other physiological and neurobehavioral alterations

- Validate noninvasive methods to monitor crew adaptations and crew-ground interactions and detect impairments in performance and behavioral health

- Develop habitability requirements for environmental parameters to ensure optimal crew alertness, sleep, and circadian function

- Validate mathematical models that optimize sleep and circadian schedules for maintaining optimal health and performance, validate effectiveness of work/rest schedules

Enabling Technologies: Behavioral Health and Human Performance

- Noninvasive behavioral health assessment and monitoring technologies
- Nonintrusive sleep and circadian function monitoring technologies
- Advanced onboard computerized cognitive self-tests
- Habitats that optimize psychosocial, sleep and circadian rhythm, and neurobehavioral adaptation

Astronaut Daniel W. Bursch, Expedition Four Flight Engineer, performs cardiopulmonary resuscitation (CPR) on a jerry-rigged "human chest" dummy in the Destiny laboratory on ISS.

1d.—How can we enable autonomous medical care in space?

Research Focus: Medical Care

As the boundaries of human space flight are expanded, the need for autonomous performance by the crew and their medical care systems and processes becomes increasingly important. The pathway to autonomy requires a systematic approach to develop the capacity to provide medical care and perform research with less input from people on Earth. The primary challenge is to ensure that the necessary medical procedures, tools, systems, and training are developed to support missions of increasing duration and distance from Earth. To this end, we work closely with the Space Flight Enterprise (SFE) Crew Health and Safety Program, which implements countermeasures and provides medical care for the astronaut corps.

To meet this challenge, the research strategy includes the development of a tool and process, the Clinical Status Evaluation (CSE), in collaboration with SFE. The CSE will systematically characterize the health and performance of the crew before, during, and after space flight; provide monitoring of the physiological and psychological adaptation of the crew; determine clinical trends for tracking health status of individuals; and evaluate risk-management strategies. It will provide the database for establishing and maintaining the acceptable levels of risk and developing the capability for autonomous medical care.

Caring for the crew during a mission is dependent on the development of efficient, minimally invasive technologies and requires the capability to diagnose and treat medical conditions and the ability to perform surgical procedures autonomously. To accomplish this, the research strategy applies a greater emphasis on collaborative efforts across biomedical and clinical components and advanced technologies. A potential enhancement is greater focus on research required for training the crews and developing medical capabilities for increasingly autonomous space flight operations.

Research and Technology Development Targets (2004–2008):

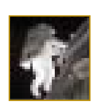
- Establish core CSE content and levels of performance that determine acceptable levels of risk, based on mission characteristics, crew roles, and responsibilities
- Determine clinical trends of space flight-induced physiological responses for health status evaluation for multiple missions up to 200 days
- Assess the effectiveness and efficiency of countermeasures for clinical issues and risks (e.g., altered pharmacodynamics, space-related decompression sickness, delayed wound healing, disrupted bone integrity, impaired fracture healing, altered behavior and mood)
- Conduct research for developing capabilities, protocols, and flight rules for medical conditions treated in flight, including EVA
- Develop and evaluate treatment regimens to restore performance and strength to preflight levels
- Identify and assess crew screening and select-in criteria and certify for 200-day ISS missions
- Adapt Earth-based medical technology for space use

Research and Technology Development Targets (2009–2016):

- Determine clinical trends for health status evaluation of physiological changes for missions up to 500 days
- Validate crew health and performance norms and countermeasures during and after long-duration space flight based on the CSE
- Demonstrate autonomous medical care capabilities and smart systems (monitoring, diagnosis, and treatment) to support medical contingencies, communication delays, and scientific operations for long-duration space flight
- Identify and assess crew screening and certification criteria for long-duration missions

Enabling Technologies: Medical Care

- Multimodal biomedical sensing, data interpretation (“smart sensors”), and transmission devices
- Sensors and nano/microtechnology devices for critical care
- Simulation, training algorithms, and devices
- Microsurgical techniques and equipment
- Data integration and real-time information processing
- Adaptive wireless and archiving technology



Earth Applications for Organizing Question 1

Enabling crews to remain healthy in space has a significant corollary with improved life on Earth. Advanced imaging, sensing technologies, and treatment modalities developed for space medicine can aid in early detection, diagnosis, monitoring, and treatment of diseases on Earth such as cancer; osteoporosis; and muscular, neurovestibular, and balance problems. The Biological and Physical Research Enterprise is committed to bringing home the accomplishments of space research, specifically adopting our findings and technology to yield the following:

- Advanced measurement devices for early and more precise diagnosis of osteoporosis and better treatment options for bone-wasting diseases
- Noninvasive technologies such as ultrasound techniques to detect and treat bone loss and muscle atrophy
- Advanced telemedicine and adaptive wireless capabilities for medical emergency situations
- Drug delivery systems
- Dietary constituents related to biomedical risks (e.g., accelerated osteoporosis)
- New drugs for motion sickness that are more effective and have fewer side effects
- Sensitive, diagnostic tests and techniques for treating balance and vestibular disorders
- Radiation health of industrial and clinical radiation workers, radiation therapies (antioxidants) for cancer patients, advanced dosimeters for industrial uses, pharmacological intervention for radiation and oxidative stress damage, and materials to shield against radiation for hazardous materials (HAZMAT) workers and first responders
- Behavioral health, performance research, interpersonal dynamics, communications, and problem solving in group settings, such as family, workplace, or school
- Sleep and circadian rhythm disturbances for health and performance of shift workers, transcontinental flyers, the military, a subset of the aging population, and millions of sleep-deprived individuals

A neurovestibular adaptation project uses eye movements produced by moving stripes to help evaluate inner-ear function.

Education and Public Outreach Highlights: Surviving on the New Frontier

If human footprints are to mark other worlds and robotic explorers are to explore the cosmos, NASA's challenge is to help the next generation of scientists and engineers develop the skills necessary to enable this exploration. Space cities cruising at warp speed and humans traveling from planet to planet with ease are not today's reality. However, we often are not aware that space travel poses hazards to human health—from bone loss similar to osteoporosis to cosmic radiation that turns cells cancerous. Studies of physiological changes, psychological alterations, and cosmic radiation are exciting fields that beckon to students and educators and lead to human exploration of the cosmos.

Throughout history, exploration has depended on—and in some cases, been hindered by—nutritional needs. Space exploration is no different. Providing the right balance of food and nutrients for the crew of an extended space mission is no less important than packing limes for early British sailing vessels. The Adopt-a-Classroom program connects upper-elementary students with space nutrition research. An essential element of Adopt-a-Classroom is the *Space Nutrition* newsletter, distributed to fourth- and fifth-grade students across the country. This newsletter provides information on astronaut nutrition and describes the careful planning and teamwork that contribute to mission success.

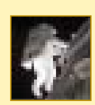
The *Space Nutrition* newsletter provides students with information about astronaut nutrition and health, space food processing, and advanced life support.

The Biological and Physical Research Enterprise education and outreach activities bridge time—extending from present-day classrooms to those of the future. A wide variety of programs is directed toward both current and future educators to assist them in developing their students' science, math, and technology skills. For example, members of the National Space Biomedical Research Institute (NSBRI), a NASA-established research consortium, train the next generation of explorers through teacher workshops, collegiate-level courses, K–12 curriculum materials, electronic materials, and informational pieces. Additionally, the Massachusetts Institute of Technology is developing materials that will become a part of regular graduate and undergraduate courses.

To help teachers relate NASA research to classroom learning, Enterprise scientists and staff regularly conduct educator workshops at teacher conventions, professional meetings, and NASA Centers.

The Morehouse School of Medicine in Atlanta mentors science teachers during a year-long residency. They work side-by-side with scientists and physicians to develop, test, and disseminate curriculum supplements on human physiological systems. The Mount Sinai School of Medicine in New York City is developing a space-based science and mathematics unit that compares human health on Earth to that in microgravity, titled "Defying Gravity: Enduring Life in Space." This project will be field tested in New York among an underrepresented and academically challenged student population.

These are only a few examples of innovative educational efforts to ensure humans can survive and thrive as we continue expeditions into the unknown.



Organizing Question 2.—How does life respond to gravity and space environments?

The force of gravity plays a major role in shaping life into its myriad forms. In addition, the radiation environment on Earth differs from radiation environments in space, because Earth's magnetic field and atmosphere shield life on Earth from some components of space radiation. What will happen as we take larger steps beyond our home planet, exposing ourselves to reduced- or microgravity with only the shells of our spacecraft to protect us? Can life—not just humans, but also the life we take with us to support us in our exploration—survive and thrive in these extreme conditions?

Today's revolution in biological technology and the increasingly rapid pace of new knowledge provide opportunities to examine the very foundations of life. Life's responses to varying conditions—including the extremes of temperature, pressure, and radiation—are revealing long-held secrets of life's capacity to adapt, thrive, and make use of environmental resources. Our strategy of extending biological research to space is supported by the report by the National Research Council (NRC) Committee on Space Biology and Medicine: *A Strategy for Research in Space Biology and Medicine in the New Century* (1998).

Using space to probe the fundamental nature of life on Earth facilitates exploration and enhances our understanding of how life responds to physical phenomena and physical forces on Earth. Studying adaptation to microgravity differentiates physical environmental influences from direct biological responses, revealing previously hidden biological pathways that are useful in developing new pharmaceuticals, combating disease, and advancing knowledge.

To elucidate the effects of space environments on life and provide an understanding of life's foundations on Earth and beyond, four detailed questions need to be answered:

The fruit fly, *Drosophila melanogaster*, is a model specimen used for genetic and developmental studies. (courtesy of Dennis Kunkel Microscopy, Inc.)

2a. How do space environments affect life at molecular and cellular levels?—focuses on the effects of microgravity, radiation, and other unique aspects of space environments on gene expression and other cellular responses, offering tantalizing clues about the effects of microgravity on life at its most fundamental levels.

2b. How do space environments affect organisms throughout their lives?—addresses the developmental, physiological, and maturation processes of life at many levels, including tissues, organs, systems, and whole organisms, providing insight into potential mechanisms to allow humans to successfully adapt to long-duration space exposure.

2c. How do space environments influence interactions between organisms?—examines the ecosystems within our own bodies and on spacecraft, as well as their optimization to support us on long journeys from Earth.

2d. Can life be sustained and thrive in space across generations?—studies living systems over multiple generations as they move beyond Earth for increasingly long periods and evolve, adapting to new niches and novel environments.

For each of these detailed questions, our approach is to use common facilities to understand and differentiate environmental influences from fundamental biological processes.

Ground.—Ground research provides the basis for flight research and broadens our fundamental knowledge. Hypergravity research using centrifuges extends knowledge of life's response to a spectrum of gravity levels. Analysis of archived specimens and data from previous space experiments using new technological approaches increases the value of the research.

Flight.—The Space Station Biological Research Project will offer ISS Flight facilities for a wide range of biological experiments with specimens ranging from single cells to living organisms such

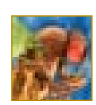
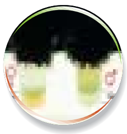
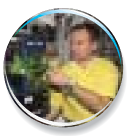


Figure 3.3

Organizing Question 2.—How does life respond to gravity and space environments?

Research Targets		Today	2004–2008	2009–2016
	*Determine how cells respond to gravity*	Data on various cell types collected in short-term studies	Develop physical and genetic models of cellular responses to space environments for at least two cell types	Develop cell-based model assays to identify cellular systems affected by space; Integrate biological effects with cell communications
	*Determine how gravity affects organisms at critical stages of development and maturation*	Incomplete life cycle and ground-based data gathered from short-duration flights	Use ground-based simulators, nanosatellites and ISS to determine gravity responses for a wide variety of organisms	Determine gravity thresholds and developmental responses in space using centrifuges on ISS
	*Understand interactions among groups of simple and complex organisms*	Ground-based virulence studies performed, lack systems supporting mixed organisms in space	Model effects of space environments on pathogenic and cooperative interactions among species	Identify microorganisms that become pathogenic or otherwise alter function in space environments
	*Determine how Earth-based life can best adapt to different space environments through multiple generations*	Preliminary multi-generation flight research performed on plants	Raise species from multiple kingdoms through several generations in flight; focus on reproductive success	Raise mammals through multiple generations in flight; investigate developmental adaptations and critical issues
Research Capabilities		**Ground labs, Shuttle, ISS**	**Ground labs, Shuttle, ISS, nanosatellites**	**Ground labs including analogs and integrated testing, Shuttle, ISS, free flyers**

OUTCOME

Ability to predict response of cells, molecules, organisms, and ecosystems to space environments

as insects, plants, and rodents. Organisms and specimens will be studied using a glovebox and an on-orbit centrifuge, that provides one-gravity experimental controls as well as detailed investigations into the effects of fractional gravity on life. Research collaborations using commercial space hardware for Space Shuttle and ISS experiments and through free-flying satellites can extend experiment capacity. Investigations performed in high-Earth orbit serve as preparatory steps to interplanetary journeys.

Flight resources are managed using a portfolio approach. Today, most resources are devoted to single-investigator-driven research. A portfolio approach to research relies on communities of investigators using model organisms to (1) allow repeat investigations for critical new discoveries, (2) decrease time from selection to flight, (3) shorten the discovery confirmation process, and (4) enhance the mission-driven nature of our life sciences research.

The following sections present the research strategy associated with organizing question 2. Each section contains research targets (near- and far-term), and a summary of enabling technologies. Earth applications are summarized at the end of the four detailed questions. The roadmap in figure 3.3 illustrates the research targets aligned to specific timeframes and a statement of the long-term outcome.

Eggs from *Xenopus laevis*, an African claw-toed frog, are shown on Earth (left) compared to the random distribution observed in microgravity (right).

2a.—How do space environments affect life at molecular and cellular levels?

Research Focus: Molecular and Cellular Impacts

Space exploration offers engineering, biological, and medical challenges resulting from exposure to microgravity, space radiation, and the host of environmental factors in spacecraft. As is true of our understanding of life on Earth, insight into cellular responses is fundamental to enabling terrestrial life to transition and thrive in space environments. Research on understanding the process of life at the molecular level is one of five interagency research and development priorities for fiscal year 2005, as cited in a memorandum for the Executive departments and agencies under the direction of the Office of Science and Technology Policy and the Office of Management and Budget.

Alterations in gravity impact cells in many ways including cell proliferation, chromosomal aberrations, gene expression, and processes of reproductive cell formation. Today, the answer to the most basic question, “How does a cell sense and respond to gravity?” remains unclear. Consequences of the physical environment must be differentiated from direct biological effects. Because complex organisms consist of many different cells and cell systems, one response is not necessarily predictive of others. Developing models of simple cells and their methods of detecting and responding to gravity are critical steps in understanding the reaction of complex organisms and their ability to thrive in space.

Outside Earth’s atmosphere and beyond LEO, humans and their supporting ecosystems are exposed to different types of radiation. The current database of the effects of charged particle radiation on cells, tissues, and animals is small, and our understanding of the mechanisms of response is limited. Important experiments examine the fundamental roles of gravity and cosmic radiation on molecular damage and repair, gene expression, cell death, and tumor induction.

Cell research is vital to extending our presence in space. Cells afford specific research advantages because they have fewer logistical demands, replicate frequently, and are a microcosm of more complex forms of life. Use of cells to understand how life responds to space environments is the first step toward the establishment of levels of gravity necessary to sustain normal function.

Investigating bacteria, fungi, plants, humans, and other animals using whole organisms or cultured cells in both ground- and space-based models enables a definitive analysis of cellular functions. Modern cell biology techniques such as analyses of gene expression, protein expression, and structure identify signals and responses arising in space environments and enable elucidation of the underlying mechanisms.

Research Targets (2004–2008):

- Analyze unique genetic, protein, and metabolic responses to gravity and space radiation
- Determine the gravity-detection mechanism in cells
- Determine the signaling pathways involved in gravity sensing, transduction, and response
- Develop physical and genetic/protein models of cellular responses to space environments

Research Targets (2009–2016):

- Integrate molecular and cellular responses to gravity with organismal function
- Determine the effects of altered gravitational environments on cellular communications
- Establish the effects of space on the morphology, structure, sub-cellular organization, and biological responses of cells

Enabling Technologies: Molecular and Cellular Impacts

- Nanosatellites for in situ analyses
- Microanalytical technologies: molecular recorders and tags, liquid protein and gene arrays, reporter-based polymerase chain reaction
- Miniaturized, autonomous systems for space biological research
- In situ imaging systems to visualize changes in cell shape and configuration
- Bioinformatics for discovery of key cellular and molecular knowledge necessary for biological organisms to thrive in space environments
- Computational models of molecular systems including protein dynamics

- Develop and validate cell-based models to identify cellular systems affected by space environments
- Determine the molecular and cellular responses to radiation in and beyond LEO as a function of exposure
- Transfer results to countermeasure conception, development, and validation

The purple sea urchin, a widely used model for studying the biology of fertilization, may provide insights into how reproduction is affected by gravity.

2b.—How do space environments affect organisms throughout their lives?

Research Focus: Life in Space

In addition to understanding the impacts of space environments at the cellular and molecular levels, it is also important to develop an understanding at the level of a whole organism. Use of genetically engineered model organisms provides knowledge of their genetic, biochemical, and physiological makeup. The effects of longer exposures to altered gravity environments, including exposure throughout all life stages, must be determined.

While some of the biological effects of space environments induce adaptation, these adaptations can be disruptive or harmful upon return to Earth, altering organismal development and affecting critical life stages. Fundamental knowledge of adaptation mechanisms is essential to countermeasure development.

Research Targets (2004–2008):

- Develop models of the process by which organisms detect and respond to gravity

- Determine gravity-induced changes and their underlying mechanisms at critical life stages in model organisms through ground studies

- Identify radiation-induced changes and investigate mechanisms of change in large and small organisms using ground-based experiments

Research Targets (2009–2016):

- Use flight experiments to separate the direct and indirect effects of gravity on organisms

- Validate findings of ground experiments with space studies on the effects of gravity-induced changes at critical life stages in non-mammalian organisms

- Determine mechanisms for the physiologically significant effects of fractional gravity

A pea pod shows the relative size of miniaturized components used for biological sensing.

> **Enabling Technologies: Life in Space**
>
> - In-flight systems and modules for growth and nurturing of higher organisms
> - In situ analysis and automated sample management/handling systems to permit remote measurements and data return
> - Miniaturized, autonomous processing and control systems for space biological research
> - Advanced fixation and cryopreservation systems
> - ISS centrifuge

- Utilize ground data to focus investigations of radiation-induced changes and mechanisms in space environments and determine the most deleterious changes

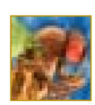
Commander Sergei Zalyotin looks at a plant growth experiment in the Zvezda Service Module on the ISS. In optimizing plant growth facilities for flight, NASA has achieved record crop yields.

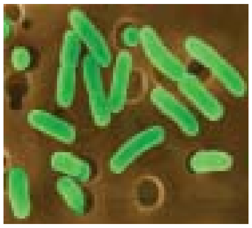
2c.—How do space environments influence interactions between organisms?

Research Focus: Ecosystems

Knowledge of the nature and dynamics of ecosystems in space environments is limited. While computational models of ecosystems on Earth do not yet include gravity as a variable, understanding gravity's influence on the fundamental processes of stable, productive closed ecosystems is essential for long-duration space travel. Closed ecological systems are preferred and perhaps necessary for life support, food production, and waste recycling. In addition, crewmembers have consistently identified the psychological benefits of plants in the mission environment, both in space and ground test venues.

The spacecraft, the astronauts, and other organisms on board carry their own ecosystems of microbes that must be understood to be safely controlled. The crewmembers, constituent members of the spacecraft ecosystem, interact with all of the other ecosystem components, from plants to microbes. Defining the nature of pathogenic and symbiotic relationships over extended periods in space and managing those relationships is critical to maintaining





Research indicates that the virulence of common bacteria, such as *E. coli* (shown above), may increase in space environments.

health and achieving control of ecosystems and requires multidisciplinary studies that examine the full lifespan of the ecosystems in question. Deciphering and then predicting and controlling the evolutionary pathways of ecosystems in space is vital.

Space-bound ecosystems must be self-sustaining communities of plants, animals, and micro-organisms. Research is needed to determine the impact of space environments on interrelationships between the organisms that populate constructed ecosystems. Organisms selected as candidates for accompanying and sustaining humans in space must withstand the impact of space-induced changes on their compatibility with organic and inorganic surroundings.

Information on ecosystem processes in extreme environments on Earth contributes to understanding ecosystem processes in space. For example, deep sea vents, summits of high-altitude peaks, hot springs, and volcanic fumaroles may reveal key elements of the plasticity and vulnerability of ecosystems. Studies of the organisms that live in such extreme environments will not only provide insight into the ability of life to adapt to space environments, but will also support the field of astrobiology and the search for life in the universe.

Research Targets (2004–2008):

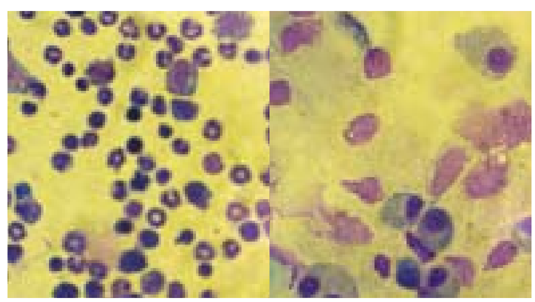
- Examine how species' differences affect ecological processes in space environments
- Design studies that determine which ecological processes are sensitive to or tolerant of the environmental conditions in space
- Use ground-based models to examine the effects of space on the interactions of pathogenic and symbiotic microorganisms with their hosts over time
- Understand the nature and course of biofilm formation and propagation in microgravity
- Identify key biological characteristics of ecological systems for long-duration human space missions
- Determine the stability of artificial ecosystems in closed environments on Earth

Research Targets (2009–2016):

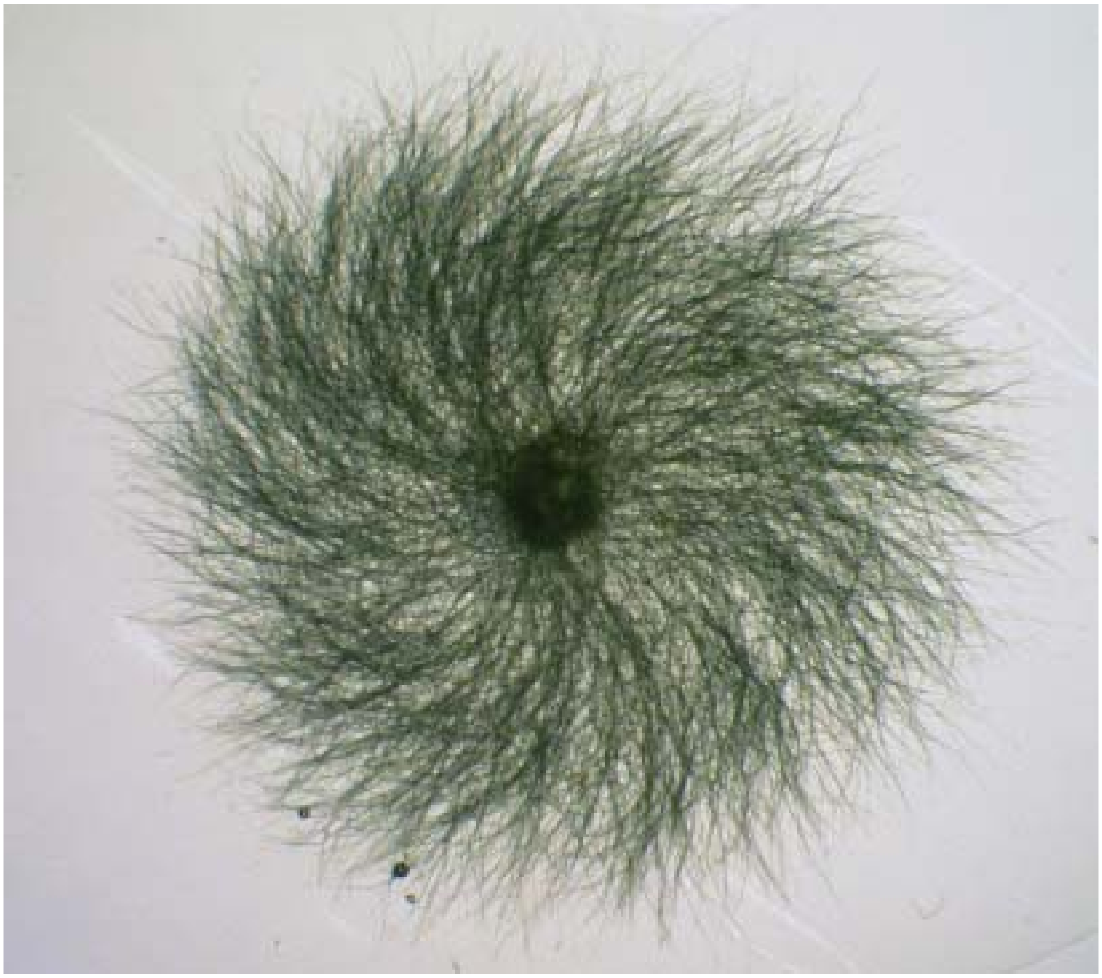
- Follow the evolution of virulent organisms in space environments using free-flying satellites testing virulence and tissue reactions
- Use engineered tissue as a host for microbial and viral growth to investigate microgravity as a selective environment in replicating viral, bacterial, and fungal populations
- Construct and test ecological systems with the potential to support long-term human space missions
- Investigate effective genetic traits for optimizing artificial ecosystems for extreme environments on Earth
- Identify microorganisms and plants with the greatest potential to provide O_2, remove CO_2, recycle H_20, and provide food for humans in space

Enabling Technologies: Ecosystems

- Models to analyze the biochemical and biophysical systems of simple and complex organisms exposed to space environments
- Models of closed ecosystems on Earth
- Free-flying satellites for work on pathogenic organisms



Cells respond remarkably fast to microgravity. After only 7–10 seconds in reduced gravity, a type of blood cell known as a macrophage changes shape, flattening out (right). When returned to Earth gravity, the cells quickly round up (left).



Ceratodon moss growth on STS-87 was expected to be random; however, a spiral pattern was observed. The spirals were observed once again on STS-107.

2d.—Can life be sustained and thrive in space across generations?

Research Focus: Generations

Life on Earth evolved in the presence of radiation and constant gravity. Are these factors essential to the emergence and maintenance of life? What changes are seen in organisms after continued presence in space? The unique environments of space provide an opportunity to address these questions. Studies of life in space need to include representatives of many types of organisms and focus on the effects of space on development and aging processes over multiple generations.

Understanding change mechanisms of organisms in space environments allows patterns of change to emerge, testing the hypothesis that radiation and gravity drive aspects of the emergence and evolution of life on Earth. Discerning changes over multiple generations in space environments is essential to reveal patterns. To accomplish this research target, both short- and long-term flight experiments are essential. Some patterns may be shared only by different groups of organisms that come from similar environments or ecologies. There may also be unique patterns of change induced by space environments that affect organisms no matter what their origin. Discerning between these two agents of adaptation may be important to enabling the movement of life beyond Earth.

Research Targets (2004–2008):

- Identify effects of altered gravity on patterns of change over multiple generations in organisms with short life cycles
- Raise organisms from multiple kingdoms (i.e., plant, animal) through several generations in space environments
- Assess changes in reproductive capacity induced by space environments

Research Targets (2009–2016):

- Raise organisms, including mammals, through multiple generations at various gravitational levels during flight with an emphasis on understanding mechanisms
- Identify patterns of change over multiple generations in organisms with longer life spans
- Determine if there are conserved mechanisms by which space environments affect organisms

The tiny worm, *C. elegans*, is used in Enterprise research to understand how organisms respond to gravity at the molecular, cellular, developmental, and behavioral levels.

Earth Applications for Organizing Question 2

Application of knowledge from space-based molecular, cellular, organismal, and ecosystem studies has potential for positive impacts on Earth. Our broad research program provides opportunities for discoveries and developments in many fields, including biomedicine, agriculture, and homeland security.

- Determining the effects of space environments at the molecular, cellular, and organismal levels benefits Earth-based medical solutions for problems such as bone loss, muscle atrophy, vertigo, wound treatment, and neurological disorders.
- Research at the cellular level contributes to understanding of bone marrow and blood cell regeneration and cancer mechanisms.
- Microbial research may lead to development of handheld biological pathogen detection devices for use in civil defense, water quality, and food safety verification.
- Knowledge of radiation response mechanisms will lead to improved safety and more effective radiation treatments for cancer and other diseases.
- Microbial ecology and evolution research complement ground-based research and will advance understanding of microbial evolution, microbial adaptations to environmental changes, evolution of antibiotic resistance, disease therapies, and bioremediation processes.
- Space-based plant research provides insight into plant growth, lignin synthesis, and metabolic pathways; improves forest crop yields, floriculture practices, paper quality; and may lead to new practices that will increase food supplies for hungry populations.

Education and Public Outreach Highlights: Planting Seeds of Exploration

Students are often most fascinated by the simplest of things like insects and plants. Everyday life that seems common can become an effective tool to teach complex scientific principles and to learn the effects of space on life forms.

Brassica and Butterflies is one of many NASA-sponsored education programs that demonstrates the relationship between NASA's research and textbook learning. *Brassica rapa* is a member of the mustard plant family and a close relative to broccoli and cauliflower. These plants have been used for research on the Shuttle, the Russian space station Mir, and the ISS. They were the first plants used in multigenerational studies in space, growing from plant to seed to new plants and seeds, all on-orbit.

The rapidly cycling variety of *Brassica* is ideal for experiments in space and Earth-based studies where limiting factors include volume and time.

Teacher professional development programs include preservice and inservice educators. Each *Brassica* and Butterfly workshop provides instruction on program concepts and techniques.

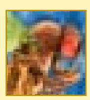
Integrated student programs enhance science understanding and improve mathematics and reasoning abilities. Here, students measure and record plant height for a graphing exercise.

The plant grows quickly, reaching a height of only 12 inches, in less than 45 days. Students can plant seeds, tend plants, pollinate flowers, and harvest the new seeds in a month.

In 1997, before the Shuttle lifted off on the STS-87 mission to rendezvous with Mir, thousands of teachers in the United States and in Ukraine were trained in workshops titled "Students and Teachers Investigating Plants in Space." During the mission, more than a million students grew plants on the ground while Ukrainian Payload Specialist Leonid Kadenyuk grew similar plants in space. NASA sponsored live television downlinks from the Shuttle and a student-focused "question and answer" period with Kadenyuk.

A follow-on teacher's guide, "LEO Then Beyond," explains the concept of bioregenerative life support systems—the use of plants to provide food to crews, remove pollution from space habitats, and regenerate oxygen and water during long-duration space missions. Students use gallon milk containers to build their own versions of the plant growth chambers. In April 2002, students used these learning tools to conduct ground experiments in parallel with plant investigations conducted on the ISS.

Seeds sprout and grow. Butterflies thrive from eating the plants. The circle of life both fascinates students and offers researchers clues about how to create oases of life on new worlds.



Organizing Question 3.—What new opportunities can research bring to expand understanding of the laws of nature and enrich lives on Earth?

This question responds to the motives that compel exploration—to deepen our knowledge of the world in which we live and to return knowledge of tangible value. The question has been examined in depth by the research community in several important studies, coinciding with the development of the ISS, and the contemplation of future missions for human exploration of space. The National Research Council (NRC) has offered recommendations on opportunities and priorities for physical sciences research in space in a number of reports over the last two decades. Plans for the future, outlined within this organizing question, draw substantially from these recommendations.

Research in space uses the unique characteristics of low-gravity and radiation environments as experimental tools to probe into the mechanisms and properties of biological and physical systems. Space researchers extend NASA's scientific reach in important dimensions, including fluid, thermal, and combustion engineering science, materials science, condensed matter and atomic physics, and biotechnology. The Enterprise programs represent a major portion of the total involvement in NASA research by academic specialties such as mechanical engineering, chemical engineering, and materials science and engineering, and substantially broaden the participation of the biology and physics communities in the space program. Their expertise is a significant asset to NASA and the Nation.

Industrial participation brings industry-sponsored researchers the opportunity to use space-based laboratories as part of their product- and process-directed projects. The presence of industrial research in space is an important step in the long-term evolution of commercial interest in the opportunities offered by a new frontier.

This image demonstrates large liquid surface instability leading to droplet ejection from a liquid layer held by a wire loop in space. The drastic reduction of the gravitational acceleration allows the investigation of large-amplitude surface tension-driven phenomena for fundamental understanding and for the development of fluid-based microgravity engineering systems. This photograph was taken by Astronaut Donald R. Pettit, the ISS Expedition Six Science Officer.

In the following pages, NASA's program to use research laboratories in space to expand our understanding of the laws of nature and to enrich lives on Earth will be described under the principal programmatic thrusts that form the framework for research planning in this area. The following five detailed questions summarize the thrusts:

3a. How do space environments change physical, chemical, and biophysical processes, the essential building blocks of many critical technologies?—uses microgravity to better understand these processes and their application on Earth, leading to better design tools in energy, materials, and communication technologies.

3b. How do structure and complexity arise in nature?—examines the origins of order in nature in a variety of settings, including grain coarsening in metals, evolution of structure in solidifying alloys, order-disorder transitions in colloidal systems, and heat transport in superfluid helium.

3c. Where can our research advance our knowledge of the fundamental laws governing time and matter?—describes the forces present in the universe and their effects on matter, achieving greater clarity and accuracy through experiments planned for the ISS and free-flying satellites, exploring concepts like the quantum properties of matter, the limits of Einstein's theory of gravitation, the properties of the electron, and other outstanding questions.

3d. What biophysical mechanisms control the cellular and physiological behavior observed in the space environment?—applies interdisciplinary research and experimental methodologies and technologies in physical and biological sciences, such as the use of fluid dynamics and

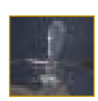
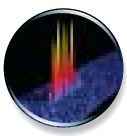
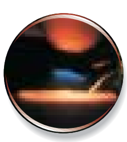


Figure 3.4

Organizing Question 3.—What new opportunities can research bring to expand understanding of the laws of nature and enrich lives on Earth?

Research Targets	Today	2004–2008	2009–2016
 *Determine how space environments change physical and chemical processes*	Research hampered by gravity-driven effects; gravity effects not understood in many technologies	Conduct ground and flight research to develop and validate models for fluid, thermal, combustion, and solidification processes	Test extended range models for heat transfer and microfluidic control, turbulent and high-pressure combustion validation; nanotechnology-based materials with enhanced and adaptive properties
 *Understand how structure and complexity arise in nature*	Limited experimental data collected on self-assembly, self-organization, and structure development processes	Conduct ground and space research in solidification dynamics, colloidal photonics, carbon nanostructures	Research new technologies for advanced photonic materials Test solidification models using industrial systems Conduct flight investigations in turbulent combustion, granular material systems, and flows
 *Understand the fundamental laws governing time and matter*	Data of unprecedented accuracy obtained in microgravity	Conduct research in dynamics of quantum liquids, atomic clock reference for space Develop technology for nanogravity satellite relativity experiments	Test Bose-Einstein condensates atom laser theories Use satellite experiments to test second-order models of general relativity
 *Identify the biophysical mechanisms that control the cellular and physiological behavior observed in the space environment*	Results obtained from Earth-based bioreactor and space-based tissue culture need validation; space-based improvements in protein crystal structures need validatior	Conduct tissue-based research and engineering in space test models for fluid-stress and cellular response mechanisms Quantify key physiological signals Complete space-based flight research and establish validation of impact on structural biology	Test control strategies for cellular response to fluid stresses Integrate NASA technologies and research with biomedical needs
 *Identify the role of research partnerships in supporting national goals*	RPC-built hardware flying; research spans broad range relevant to Earth-based industrial application	Increase focus on NASA needs, while maintaining industrial partnerships Direct research toward Earth- and space-based applications Apply capabilities and experience of RPCs in building space flight hardware to new ISS facilities	Achieve backing by industrial partnerships toward exploration opportunities Apply RPC approach to new flight opportunities, LEO, and beyond
Research Capabilities	**Ground labs, Shuttle, ISS, KC-135 aircraft**	**Ground labs, Shuttle, ISS, KC-135 aircraft**	**Ground labs, Shuttle, ISS, KC-135 aircraft, free flyers**

OUTCOME

Application of physical knowledge to new technologies and processes, particularly in areas of power, materials, manufacturing, fire safety

New insights into theories on fundamental physics, physical/chemical processes, and self-organization in nature

transport analysis to quantify the effects of gravity on living tissues; applies biological principles to new technologies in areas such as biomimetic materials.

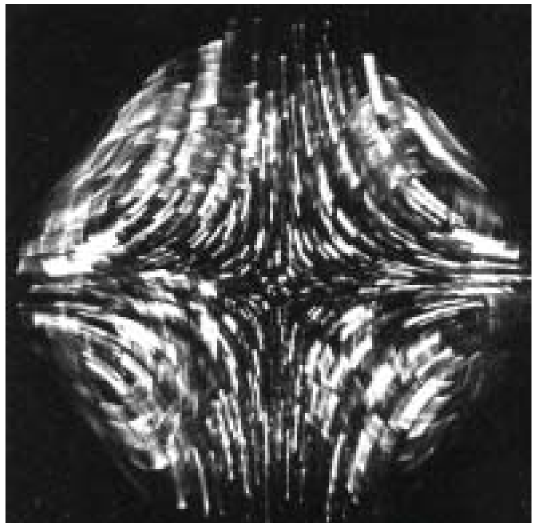
3e. How can research partnerships—both market-driven and interagency—support national goals, such as contributing to economic growth and sustaining human capital in science and technology?—fosters the use of the environments of space to advance agribusiness, materials science, biotechnology, communications, and other economic opportunities for the private sector and to assure the development of a workforce capable of meeting the aerospace challenges of the future.

Each of the five detailed questions has associated research targets (near- and far-term), and represents an interdisciplinary research effort involving integrated space- and ground-based research currently involving as many as a hundred individual investigations at many institutions. Research priorities established through recommendations from the NRC (see appendix 2 for listing of NRC reports), our advisory committees, and advice from the community through workshops and other forums have defined a set of research topics from which our targets are derived. The research targets represent aggregated summaries of NASA's expectations for the research supported under these thrusts, recognizing that many of the most significant advances of basic research have been the result of unexpected discoveries. Earth applications are summarized at the end of the five detailed questions. The roadmap in figure 3.4 illustrates the research targets aligned to specific timeframes and a statement of the long-term outcomes.

3a.—How do space environments change physical, chemical, and biophysical processes, the essential building blocks of many critical technologies?

Research Focus: Physical and Chemical Processes

When people leave Earth, they leave behind the powerful influence of one of the great constants of life and technology—the effect of Earth's gravity. Space-based research opens a new window into the principles of physical, chemical, and biophysical processes, giving researchers an unprecedented opportunity to increase understanding and advance Earth-based technologies. This effort makes significant contributions to the new materials, power generation, and manufacturing technologies of the 21st century.



Photograph of laser-illuminated tracer particle motion within an oscillating free liquid drop. Resolving the details of the behavior of totally free liquids in low gravity greatly impacts our understanding of a host of natural and industrial processes based on dispersed fluid systems.

The Enterprise continues to build on these scientific gains with notable advances in many of its research areas. For example, the theories of material solidification and crystal growth processes have proven to be directly relevant to commercial processes such as castings and semiconductor production and have a direct impact on metal-cutting tool companies and jet engine manufacturers. Nationally prominent investigators have research projects ranging from fluid flows impacted by surface tension gradients to the dynamics of multiphase and complex fluids with applications from oil reservoir modeling to space technologies. An increased fundamental understanding of the chemical kinetics of variations in flames and flame length led to revisions of both basic theory and college textbooks in combustion science. Unique experimental data obtained in low gravity from studies in smoldering, flame spread, radiative transfer, and soot production have benefited NASA's fire safety procedures and advanced knowledge of the combustion processes on Earth.

NASA research in physical and chemical processes is conducted primarily by mechanical, chemical, and materials engineers, and is supported on the ISS by the Combustion Integrated Rack, the Fluids Integrated Rack, the Materials Science Research Rack, and several instruments developed by our international partners. Experiments to be conducted on the ISS before 2008 include models of soot formation and spray combustion in diesel engines, fabrication of composite materials, heat transfer, and fluid mechanics.

Research Targets (2004–2008):

- Complete analysis, validation, and implementation of soot formation models
- Develop dataset for spray combustion modeling; improve understanding and control of gaseous flames
- Validate physics-based models of nucleate boiling with microgravity data
- Develop and validate predictive models for flow and wetting in vessels, microchannels, and soil pores
- Validate models of composite solidification with microgravity experiment data
- Refine manufacturing technology for fabrication of sintered materials

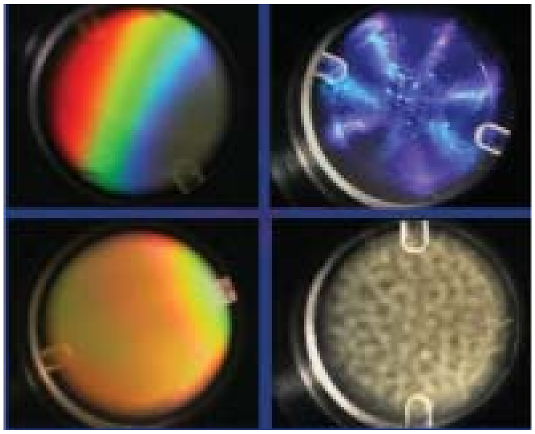
Research Targets (2009–2016):

- Validate large-scale models of turbulence in gaseous flames through flight experiments
- Validate models of high-pressure and spray effects and apply results to practical combustion systems
- Demonstrate technologies for high-efficiency enhanced vapor removal heat transfer on Earth in laboratory-scale models
- Develop design tools for free surface flows in microfluidic controls and fuel cells based on liquid-solid wetting physics
- Explore physics of nanotechnology-based self-healing materials, power generation, and energy conversion concepts through flight experiments

Enabling Technologies: Physical and Chemical Processes

- High-definition video downlink
- Space-efficient containment systems for on-orbit anomaly response
- Compact high-power laser Doppler velocimetry and spectroscopy
- Flexible crew training tools
- System tools for efficient certification of flight readiness and safety reviews
- Experiment-level robotics for enhanced teleoperations

Flames can grow and spread in space under conditions unlike those on Earth, motivating research like this experiment on a flame spread over a surface in a low-velocity forced flow. The results will impact our ability to prevent and extinguish undesired fires.



This series of images, taken aboard the ISS over 35 days, shows the evolution of a colloidal solution. Better control of the self-assembling process in colloids will allow the manufacture of potential new light-based communication technologies.

3b.—How do structure and complexity arise in nature?

Research Focus: Fundamental Mechanisms of Order

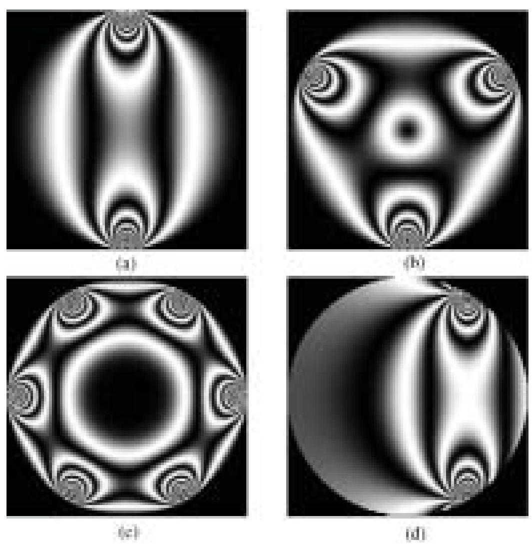
Complex systems research examines the dynamics of interacting elements and the patterns and structures that result from those dynamics. This field seeks to explain and predict how order arises from seemingly chaotic interactions. The underlying physics has such broad significance that theories are applied in areas as remote as atmospheric turbulence and traffic modeling. The advent of large-scale computing provided the computational basis for recent progress in theory, but fundamental experimental data are limited. The scientific challenges associated with complex systems are daunting, but they hold the key to a deeper understanding of many natural environmental processes, and they will provide the technological approaches for the design and fabrication of advanced intelligent materials.

The study of self-organizing systems includes both ground-based and space-based research. The ground-based work develops models for transitions to ordered states and the explanations for evolution of structure in complex systems such as solidifying alloys and particulate-laden and reacting flows. Space research provides opportunities for scientists to conduct benchmark experiments with unparalleled clarity. Planned and current projects examine coarsening of solid-liquid mixtures of metals, pattern formation in alloy solidification, the mechanics of soil failure under stress, flow of sand grains, and the mechanics of flowing foams. Colloidal crystals, formed by a self-assembly process from micron-sized particles, are the subject of intense interest in the applied physics community because of their potential as the basis for optical signal processing technologies. The Fluids Integrated Rack holds experiments on colloid physics in the light microscopy module and on the physics of particulate transport in the granular flow module. ISS research on solidification dynamics and pattern formation is centered on the Materials Science Research Rack, a cooperative development between NASA and the European Space Agency.

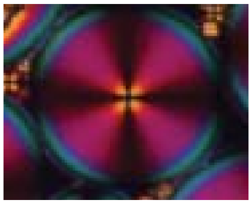
Research Targets (2004–2008):

- Test established theories of phase transitions, self-assembly, and solidification dynamics

- Complete a series of flight experiments on microstructure formation to obtain a benchmark establishing the fundamental principles that govern the selection of microstructure and length scales in alloy solidification



Research showing stress distribution in granular media helps establish better models for sand and soil behavior on Earth, and in extraterrestrial environments.



The orientation of the molecules in a liquid crystal is revealed by this view through polarized light. The tendency of objects to self-organize is one of the central issues of physics and is at the foundation of living systems.

- Complete theoretical models describing the origins of structure in particulate-laden and reacting turbulent systems

- Develop and demonstrate new experimental technologies for materials research in microgravity to explore the characteristics of metallic and oxide glasses, colloidal crystals, fullerenes, and other advanced materials

- Establish physics required to validate strategies to make colloidal crystal-based photonic devices

Research Targets (2009–2016):

- Incorporate initial flight results into new processing technologies for advanced aerospace materials

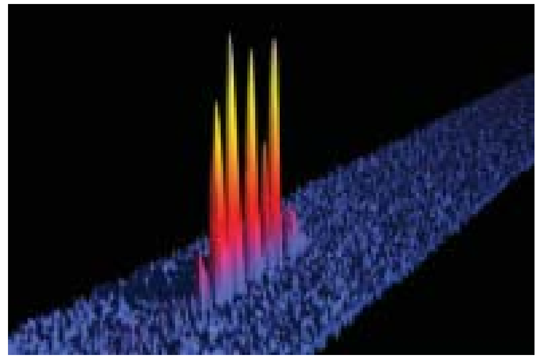
- Validate models describing the dynamics of turbulence and structure in complex and reacting systems through flight experiments

- Test questions underlying microstructure formation, self-assembly of colloidal photonic devices

Enabling Technologies: Fundamental Mechanisms of Order

- Nuclear Magnetic Resonance Imaging and X-ray tomography for dynamic structure resolution to study self-assembly and structural templating
- Laser tweezers for particle positioning and force measurement to probe the free energy landscape of self-assembling structures
- Compact one-micron resolution real-time video
- Millikelvin-control thermostat
- Compact SQUID thermometry for high-precision thermodynamic characterization of cooperative behavior and quantum effects in superfluid helium
- Picowatt thermal control for superfluid helium research
- Space-efficient containment systems for on-orbit anomaly response
- Flexible crew training tools
- System tools for efficient Certification of Flight Readiness and safety reviews
- Experiment-level robotics for enhanced teleoperations

- Test concept of "universal characteristics" of disordered states, like glasses, colloidal fluids, and granular systems



Bose-Einstein condensates can develop instabilities that produce soliton or single pulse waves that traverse the length of the condensate, as seen in this computer calculation. Bose-Einstein condensates are a newly discovered state of matter.

3c.—Where can our research advance our knowledge of the fundamental laws governing time and matter?

Research Focus: Fundamental Physics

The central objective of research in this area is to understand the laws that govern the behavior of the physical universe, represented by models describing the forces present in the universe and their effect on matter. Achieving greater clarity and accuracy in these models increases understanding of the universe itself and provides tools to create new capabilities. The space environment enables unprecedented precision in the measurement of physical constants, allowing exploration of concepts such as the breakdown of Einstein's theory of gravitation and the properties of the electron. The capability for lasers to levitate and position atoms and molecules at extremely low temperatures opened atomic physics, providing possibilities for the manipulation and application in areas like quantum computing, quantum data storage, and highly precise clocks. Microgravity also enables scientists to examine the characteristics of quantum fluids, primarily low temperature helium, which provide the best models available to physicists interested in understanding superfluidity, cooperative phase transitions (superconductivity), and other priorities of contemporary physics.

Our research explores condensed-matter, atomic, and gravitational physics. Condensed matter physics focuses on phase transitions in helium, using the low temperature microgravity physics facility aboard the ISS. Atomic physics research begins with the ISS Primary Atomic Reference Clock in Space (PARCS). Gravitational physics focuses on satellite-based experiments projected for the early part of the next decade. Satellite-based or "free-flying" missions could enhance the Enterprise's research capabilities in experimental physics. We may address some of the most compelling challenges in physics, such as the nature of gravity, unified field theory predictions of other mass-mass interactions, the nature of the dark matter and its relation to gravity, and the relation of gravity to quantum mechanics.

Research Targets (2004–2008):

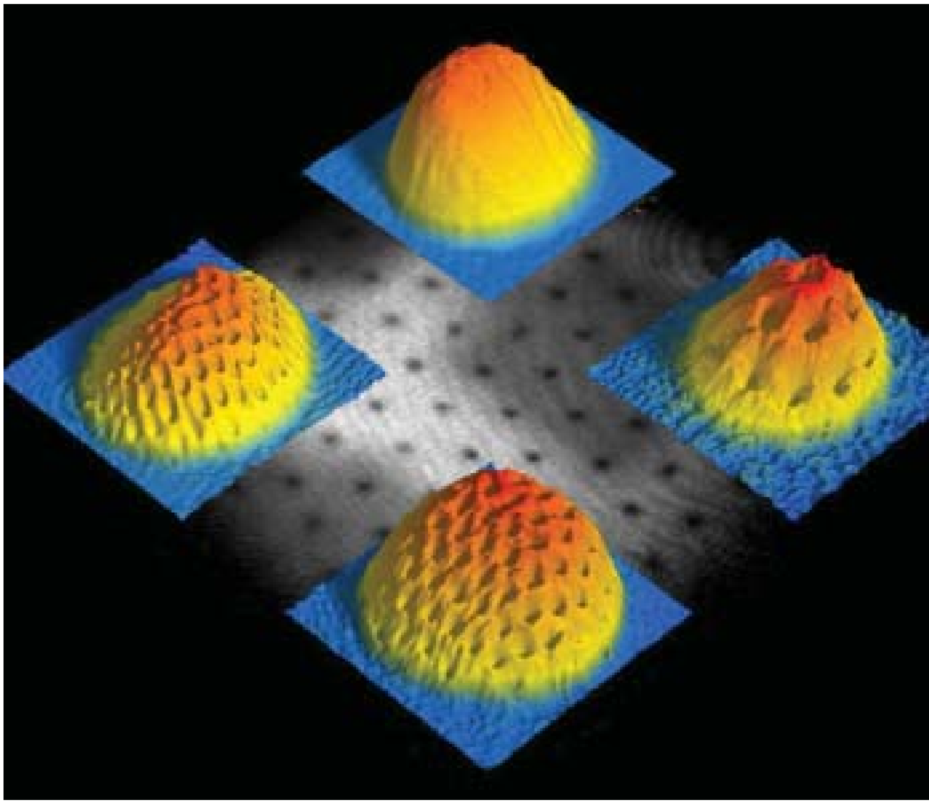
- Develop the flight facility and experiments for a coordinated series of investigations on the superfluid transition of helium
- Develop technologies for space-based atomic condensate experiments
- Develop new ultraprecise clock technologies for relativity experiments aboard the ISS

Research Targets (2009–2016):

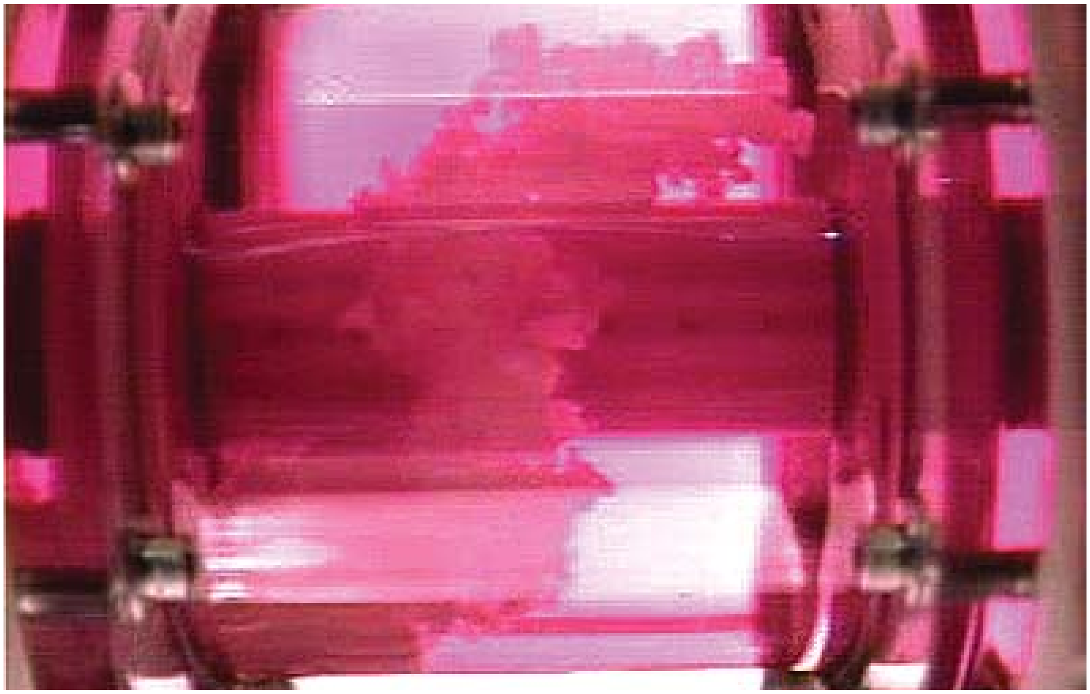
- Create new forms of matter through ultracold atom technology, such as Bose-Einstein condensates
- Test theories of atom lasers
- Fly state-of-the-art tests of inverse square law and other fundamental postulates of physics
- Launch first free-flyer missions examining the basis for a unified field theory of space-time

Enabling Technologies: Fundamental Physics

- Drag-shielded satellite designs for subnanogravity experiments
- Low-noise accelerometry
- Micronewton thrusters
- High-power long-lifetime lasers
- Diode lasers suitable for cesium and rubidium energies
- Space-flight ultrahigh vacuum components
- Miniature cryogenic valves
- Sub-Kelvin coolers



This computer image shows ordered arrays of quantum vortices arising from quanta of angular momentum in a Bose-Einstein condensate. The understanding of this phenomena could lead to insight into the dynamics of stars.



Prostate tumor cells are being grown in a rotating wall bioreactor in this image from video downlink during the STS-107 mission. The cells can be seen aggregating into large masses of tissue many times the size of comparable Earth-grown prostate cells. The research is performed to develop better cancer models and to test drug therapies as realistically as possible.

3d.—What are the fundamental biophysical mechanisms that control the cellular and physiological behavior observed in space environments?

Research Focus: Biotechnology

Using an interdisciplinary approach to research, applying both physical and biological sciences to complex problems in biotechnology, NASA has made significant contributions in the areas of tissue engineering, biomolecular physics, biophysical separation technology, and biological macromolecule crystallization. Research in tissue engineering produced the NASA bioreactor that controls mechanical stress on mammalian tissues during culture. The Enterprise's ground-based, biophysical research is conducted across a spectrum of research disciplines in the physical and biological sciences. For example, NASA collaborates with the National Institute of Child Health and Human Development (using the bioreactor), the National Eye Institute (applying fluid physics research to the detection of cataracts), and the Food and Drug Administration (developing technologies for blood glucose levels).

The ground-based program is critical to the flight program in cell and tissue culture. The program develops strong candidates for flight experiments, maturing within one to two years of flight and incorporating recent developments in the rapidly evolving world of biomedical science. Interactions of the physical environment with living tissue are at a very early stage of understanding. Microgravity studies support cell and tissue culture-based experiments using instruments developed in partnership with industrial participants and international partners. A high priority is research using complex three-dimensional tissue growth; results show that space-based tissue culture technology has the potential to produce nearly organ-size masses of mammalian tissues.

NASA is closely evaluating the progress of the biological crystal growth program and is assessing its value to the structural biology community. The NRC in *Future Biotechnology Research on the International Space Station* (2000) recommended that NASA allow the researchers several years to evaluate the potential of space-based crystal growth to assist in the crystallization of challenging proteins and complexes.

Research Targets (2004–2008):

- Establish and validate models for the cellular mechanisms responsible for adaptation to fluid stresses

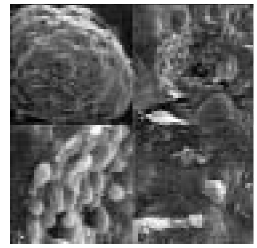
- Develop technologies for in vivo quantification of key physiological signatures
- Develop and operate first-generation tissue engineering research facilities in microgravity, allowing the national community to validate results
- Refine technologies for Earth-based bioreactors, verify stress-reduction analog to space flight
- Establish and complete validation experiments demonstrating value of microgravity-based crystal growth to structural biology
- Develop new technology for high-productivity crystallization on ground and in microgravity
- Develop criteria capable of 80 percent accuracy in predicting success of microgravity-based experiments

Research Targets (2009–2016):

- Develop and test control strategies for cellular response and transport changes under fluid stress
- Integrate NASA technologies and expertise in the physical sciences with biomedical research needs through institute-based interactions. Successfully transfer 10 technologies or capabilities to specific problems in health care
- Extend space station research to complex and functionally differentiated tissues, such as tumor models, to study normal and neoplastic development
- Automate flight-based crystal growth to serve national community
- Develop definitive screening criteria for flight-candidate proteins

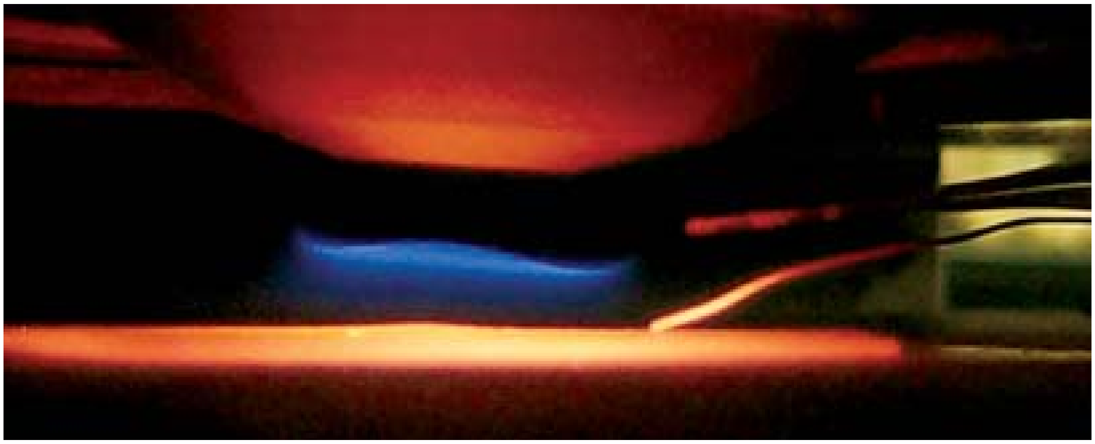
Enabling Technologies: Biotechnology

- On-orbit rotating wall bioreactors
- Culture media purification and recycling
- Trace metabolite analysis
- High-thermal-capacity cryofreezers
- Compact protein crystal growth devices
- Cryopreservation tools for protein crystals
- On-board X-ray characterization of crystal quality



Electron microscope images of breast cancer cells grown in the rotating wall bioreactor show the high degree of differentiation and structural development that can be attained using this technology.

Astronaut Don Thomas conducting an experiment using the Microgravity Science Glovebox facility. The ISS Microgravity Science Glovebox has been operational since 2002.



A blue flame burns on a solid surface at the start of a commercial experiment evaluating the effectiveness of new combustion catalysts.

3e.—How can research partnerships—both market-driven and interagency—support national goals, such as contributing to economic growth and sustaining human capital in science and technology?

Research Focus: Research Partnerships

Historically, the research challenge associated with this question was to demonstrate to industry the competitive advantage of the space environment, thereby creating new technology and enabling experimentation. The fields of commercial research included:

- Biotechnology (plant-based pharmaceuticals, increased antibiotic production rate, protein crystal growth, microencapsulation of drugs)
- Agribusiness (improved crop development and enhanced wood products through research in lignin formation)
- Materials processing (improvements in casting processes, fire-suppression technology, fiberglass, and catalysts)

This program was implemented through Commercial Space Centers (CSCs), nonprofit partnerships of commercial, academic, and governmental entities that conduct space research and development projects. Faculty members and students perform research in partnership with industry, while industrial partners carry out the commercialization. The 15 CSCs, located primarily at universities around the country, work together with 157 active industrial partners in this effort.

The program is undergoing a transition. The CSCs have recently been renamed Research Partnership Centers (RPCs) in order to reflect a new purpose. The RPCs' focus will be to further NASA's mission by establishing industry-university-government partnerships making use of NASA, academic expertise, and industry market knowledge and investments. This dual-use approach provides excellent opportunities to leverage the limited space flight experiment availability and naturally positions the research and technology for industrial applications.

Examples of dual use dominate the research targets described below. Improvements in digital television benefit the needs of the ISS vehicle and its associated research, other Federal agencies, and the Nation's commerce. Similarly, any advances in therapies to reduce the calcium loss experienced by the space-based crew are very likely to benefit people with osteoporosis, supporting NASA's exploration efforts and human health on Earth. Hence, research conducted by the RPCs is in support of advances in particular fields relevant to NASA's Mission, as well as to the missions of other Federal agencies, such as National Institutes of Health, Department of Energy, and Department of Defense. The Enterprise already has established research relationships with more than 40 Federal agencies in pursuit of mutually beneficial research or exchanges of technical expertise.

Research Targets (2004–2008):

- Develop abilities to prevent/replace calcium loss from human bones through research of Osteoprotegerin
- Develop space radiation-hardened HDTV, named HDMAX, for joint use by NASA and industry
- Develop hyperspectral imagers, cameras that image in both the UV band (200–400 nanometers) and in the IR band (900–1700 nanometers), for use in meat inspection, agriculture, and space imaging applications
- Develop water mist fire suppression for use in spacecraft as well as for buildings, ships, and aircraft
- Develop accurate, low-cost, and light-weight star trackers for satellite attitude measurements

Research Targets (2009–2016):

- Develop high-speed gyros for bearings/sensor control and for multidirectional composite fly wheels
- Develop multi-junction solar cells with 30 percent efficiency after 10 years (compared to 12.6 percent currently on ISS)
- Develop nanoparticles (resin beads) to purify air for applications in spacecraft environmental systems and for better control of micro-organisms in space
- Demonstrate the performance and robust nature of controlled environment technologies for the production of crops in space
- Develop polymer/zeolite fuel cells for advanced space power systems
- Develop and space test an elastic memory composite hinge for deployment of solar panels and other satellite components
- Develop and space test a smart sensor/beacon technology for autonomous rendezvous and docking in space

Enabling Technologies: Research Partnerships

- Advanced batteries and flywheel energy storage for long-duration space flights
- DNA microarray for gene filtering
- Hybrid communication network for satellite and wireless system improved connectivity
- Hyperspectral imagers for noninvasive medical diagnostics, and tracking sealants in metal bonding of materials
- Next-generation closed environment systems for multi-generation plant and animal research
- Special furnaces for zeolite crystal growth and combustion research
- On-orbit camera systems to record and downlink real-time research data

Levitating high-purity molten materials allows for remote measurements of physical and chemical properties. These measurements are crucial to understanding the properties of molten materials and to the modeling of industrial materials fabrication processes. This technology is currently fully operational on Earth.

Earth Applications for Organizing Question 3

Space research brings new experimental tools and a new perspective to the challenges faced by scientists and engineers. Investigators with different areas of expertise address problems with the highly productive approach of interdisciplinary research to create technological advances—from the growth of semiconductor crystals for integrated circuits to the design of bioreactors in use by over 300 biomedical research laboratories around the world. Research challenges include developing:

- A better fundamental understanding of physical and chemical processes to improve manufacturing technologies and processes, and to develop new materials
- Liquid-phase sintering applied to process improvements to substantially reduce defect and failure rates
- Flight research on combustion processes to significantly improve combustor design concepts
- Concepts for high-efficiency heat transfer, such as free surface flows applied to fluid management technologies in lab-on-a-chip designs
- Pattern formation during solidification to enable better control of materials produced by metal casting
- Studies of self-assembly in colloidal systems to reveal characteristics of a class of photonically active colloidal crystals yet to be fabricated on Earth
- Studies of the characteristics of granular flows to verify models for various applications, from industrial processes to the migration of sand dunes
- Long-term applications for matter-wave holography, one of the new directions in atomic physics, including the teleportation of matter, quantum computing, quantum data storage, and switchable states achievable in low temperature atomic spectroscopy
- Improvements in the tools used to obtain the structures of biological molecules, diagnostic technology for the early detection of cataracts, and tissue culture technologies now widely used for biomedical research in infectious disease, cancer therapy, and other health priorities
- Use of microgravity-grown tissues as models for normal and neoplastic development to support basic research in the processes of development and differentiation

As stated earlier, NASA's research partnerships yield significant industrial results specifically intended for application on Earth. Products and services cover a range of industries, including agriculture, biotechnology, and materials processing. Potential Earth benefits of NASA research partnerships include:

- Treatment for osteoporosis and low-bone density
- Ophthalmic laser systems to treat diseases of the retina
- New and enhanced food and other plant-derived products
- New approaches to bone implants of biodegradable materials that provide strength while the bone heals and reabsorbs into natural bone over time
- Biosensors to control hydrocarbons, ethylene, and other pollution-causing elements
- Detection of pathogens, such as fungal, bacterial and viral contaminants, in air, food, and water
- Demonstration of novel fire-suppression systems
- Demonstration of high-efficiency solar cells for power generation
- DNA microarrays for genomics research
- New and improved materials for flexible, flat-panel displays

Education and Public Outreach Highlights: Launching the Journeys of Future Spacefarers

Voices of student researchers who had just seen their first space experiments launched into orbit on NASA's Space Shuttle resounded with pride. More than 140 students, educators, and parents attended the STS-107 launch of the Space Shuttle Columbia on January 16, 2003. These invitees represented thousands of students from 37 schools in 9 states and 8 countries who were involved in a suite of educational projects before and during the mission to study various topics from insects to nutrition. While the student experiments were lost with Columbia and her valiant crew, the legacy of this work is the development of a new generation of scientists and engineers who understand the excitement and challenges of NASA's Vision and Mission.

"Our goal was to make this mission part of classrooms around the world," said one of the NASA outreach leaders who organized this project. "We wanted to involve students in space research tied directly to school subjects and demonstrate how space research affects people every day."

The student researchers sent a variety of living organisms into orbit, including fish, silkworms, seeds, shrimp, cells, bees, spiders, and ants. They studied how living in microgravity changes astronauts' nutritional requirements, living cells, and the growth of inorganic crystals. This knowledge can enrich life on Earth and contribute to the safe exploration of space.

Students involved in research on the ISS are focused on these same goals. For example, more than 700 students and teachers from 12 states and Puerto Rico have prepared samples for Biological Crystals in Space, a student flight program that made four trips to the ISS. On Earth students loaded samples in small tubes, which were then frozen and stored until launch. As the samples thawed in space, they formed crystals. The crystals were returned home for scientific analysis, and through a Web site, students monitored the analyses of the crystals. This program brought new perspectives to learning about biological substances and how the laws of gravity mold and shape biology and chemistry.

"These opportunities open the students' eyes to so much of the world beyond," said a science teacher from one of the participating schools. "Many of my students didn't know much about space, and these educational opportunities expose them to careers and different areas of science conducted in space."

A student tests the Mechanics of Granular Materials demonstration device at the STS-107 Education and Outreach launch event.

Many education activities simulate the research of NASA-funded investigators. The Enhanced Gaseous Nitrogen Dewar program was created by a scientist working on macromolecular crystal growth.

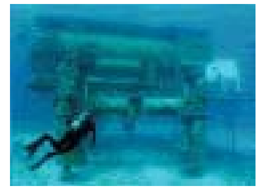
Organizing Question 4.—What technology must we create to enable the next explorers to go beyond where we have been?

As humans embark on missions of greater duration and distance, we must extend our current technological capabilities to achieve greater autonomy, efficiency, and reliability. Future explorers must be equipped with a spectrum of technologies to support and protect life during travel and utilize available resources at their destination. New technologies—vital to the extension of human life beyond LEO—must function under variable gravity conditions, guarantee crew health and safety, and enable optimal performance throughout the mission.

The Enterprise research strategy progresses iteratively toward highly efficient, habitable systems capable of maintaining an acceptable environment. This environment—air, water, food, thermal, and energy—sustains and protects human health and safety during all phases of a mission and mitigates subsequent effects from exposure to space flight hazards (e.g., environmental contaminants, radiation). Equally important are technologies that integrate across the spacecraft subsystems (including humans) to ensure optimal productivity. The research strategy focuses on specific deliverables and outcomes, developed and verified through a maturation process using a set of increasing technology readiness levels. Risks and associated critical technology research questions for ensuring habitable environments during space flight have been identified in the *Bioastronautics Strategy* (2003). Our approach is consistent with numerous reports: the National Research Council (NRC) reports *Advanced Technology for Human Support in Space* (1997) and *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies* (2000), as well as the National Academy of Science Institute of Medicine report *Safe Passage: Astronaut Care for Exploration Missions* (2001).

This artist's rendition of a self-supporting habitat on the Moon portrays the possibility for technological advances to lead to greater autonomy, efficiency, and reliability. (courtesy of John Frassanito and Associates)

The Biological and Physical Research Enterprise utilizes laboratories, analog environments, and simulators to develop, test, and verify technologies for advanced missions. Essential facilities, test beds, and high-fidelity simulators verify component, subsystem, and system performance. Analog environments such as Antarctic research stations and undersea habitats (e.g., NASA's Extreme Environment Mission Operations—NEEMO) provide resources to develop, test, and verify human performance capabilities, operational procedures, and technologies. Other examples of special facilities include the anthropometry and biotelemetry lab, the Graphic Research and Analysis Facility, and closed environmental chambers for life support and human performance testing. Fully integrated test bed activities will determine and verify the effectiveness of the complete system. New ground facilities will examine and integrate in situ resource extraction, manufacturing techniques, and energy sources.



NEEMO is an undersea habitat that serves as a special training facility for astronauts.

As a precursor to space flight-validated technologies, the Enterprise uses the following: aircraft flying reduced-gravity trajectories (parabolic flight), drop towers, the Shuttle, free-flyers, and a potential ISS facility dedicated to Advanced Human Support Technology (AHST).

Strong partnerships established through our intramural and extramural research communities, universities, the private sector, and other Government agencies help to develop and deliver these subsystems. Contributions from our partners span the entire research and technology development process, which includes the initial development of concepts, prototype development and testing, fabrication, and final verification.

To enable future explorers to travel further in space than before, the following four detailed questions must be addressed:

4a. How can we enable the next generation of autonomous, reliable spacecraft human support subsystems?—discusses the research strategy for life-support systems necessary to sustain crews for extended periods.

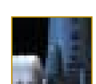
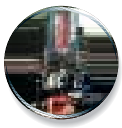
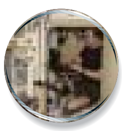


Figure 3.5

Organizing Question 4.—What technology must we create to enable the next explorers to go beyond where we have been?

Research Targets	Today	2004–2008	2009–2016
 *Increase efficiency through life-support system closure*	Current ISS baseline is a 90-day resupply Components with improved efficiency are the focus	Develop technologies that lower Equivalent System Mass (ESM) Perform integrated testing of lower ESM life-support technologies and subsystems in relevant environments	Perform onorbit validation of critical components and certification of life-support technologies for missions beyond LEO Perform integrated testing of life-support systems with humans in the loop
 *Enable engineering systems and advanced materials for safe and efficient space travel*	High-mass/cost, low-performance materials used Understanding of low- and partial-gravity issues incomplete	Develop and test low- and partial-gravity fluid and thermal engineering systems Develop and test design tools for advanced materials and in-space fabrication, and validate on ISS	Conduct ISS experiments to test prototype engineering systems Complete development of advanced materials for radiation-shielding solutions Validate prototype low- and partial-gravity resource-generation technologies
 *Enable self-supporting and autonomous human-systems for performance in habitable environments*	Predictive methods and models limited for habitability analysis, information management, crew training, multi-agent team task analysis, integrated human systems engineering	Define and develop habitats that optimize human performance Develop tools and models for human-systems integration	Validate habitat designs for multiple missions Validate human-system design simulation Deliver validated design requirements and integrated simulation tools for multiple missions
 *Develop advanced environmental monitoring and control systems*	Technologies exist for partial monitoring of ISS environment Individual sensors developed	Develop sensing capabilities for 90 percent of existing air Spacecraft Maximum Allowable Concentrations (SMACs) Develop sensing capabilities and SMACs to monitor water Develop autonomous controls architecture design	Develop miniaturized, real-time, efficient sensing capabilities for air and water Validate integrated systems
Research Capabilities	**Ground facilities, simulators, Shuttle, ISS, KC-135 aircraft**	**Ground facilities, Shuttle, ISS, KC-135 aircraft**	**Integrated ground test facilities, Shuttle, ISS, KC-135 aircraft, free flyers**

OUTCOME

New technologies that provide for more efficient, reliable, and autonomous systems for sustainable human presence beyond low-Earth orbit

4b. What new reduced-gravity engineering systems and advanced materials are required to enable efficient and safe deep-space travel?—identifies technology options to provide solutions for a range of challenges, such as in-space fabrication utilizing in situ resources and recycled materials.

4c. How can we enable optimum human performance and productivity during extended isolation from Earth?—presents the research strategy to enable crews in habitable environments far from Earth to be self-supporting, autonomous, and productive.

4d. What automated sensing and control systems must we create to ensure that the crew is living in a safe and healthy environment?—discusses the research strategy to provide future spacecraft and space habitats with improved, miniaturized networks of integrated sensors for environmental monitoring and control.

Advanced air revitalization systems are capable of generating oxygen and reducing carbon dioxide, thus offering a greater degree of closure.

The following sections present the research strategy for assuring human health, safety, and productivity associated with organizing question 4. Each section contains research targets (near- and far-term). Earth applications are summarized after the discussion of the detailed questions. Embedded in this organizing question are the essential technologies that enable human space exploration; specific enabling technologies are not highlighted in a sidebar. The roadmap in figure 3.5 illustrates the research targets aligned to specific timeframes and a statement of the long-term outcome.

Integrated testing facilities, such as the Life-Support Systems Integration Facility shown here, test the effectiveness of closed life-support systems and human performance.

4a.—How can we enable the next generation of autonomous, reliable spacecraft human support subsystems?

Research Focus: Advanced Life Support

Exploring beyond LEO and making use of resources discovered in new environments requires the basic tools already developed on Earth for energy production and the recycling of essential life-support components (e.g., air and water). These basic tools have been developed and optimized on Earth, but biological and physical processes often perform quite differently in reduced-gravity environments. Over the next 10 to 15 years, the Enterprise will build the enabling knowledge and technology base for exporting the technology processes developed on Earth to new, reduced-gravity environments.

The primary challenge for life-support systems is to move from largely open systems that require frequent resupply to closed systems that recycle air, water, and waste. Advanced life-support systems and subsystems must be developed based on a thorough understanding of the underlying biological and physical processes involved, including sensitivity to gravity, multiphase flow, microbial dynamics, and heat and mass transport processes. The resulting systems must require less power than current systems, be highly reliable and autonomous, and be physically smaller than current systems.

Another challenge is to develop advanced EVA systems, including a protective suit optimized for use on planetary surfaces. It will be critical to develop portable life-support systems for EVA that save consumables and meet requirements for CO_2, humidity, and trace contaminant removal with regenerable closed-loop thermal control, passive and active radiation shielding, and monitoring capabilities for crew health purposes.

Research and Technology Development Targets (2004–2008):

- Develop reliable, lower system mass air revitalization, water recovery, food production and processing, waste processing, and resource recovery systems
- Identify and address issues of variable gravity performance through space flight research and evaluation
- Develop integrated systems models and perform relevant trade studies of different subsystems
- Verify next-generation life-support technologies for air, water, and waste processing in relevant Earth-based analog environments
- Develop models and conduct flight experiments to validate multiphase flow and thermal-management technologies needed for new life-support systems

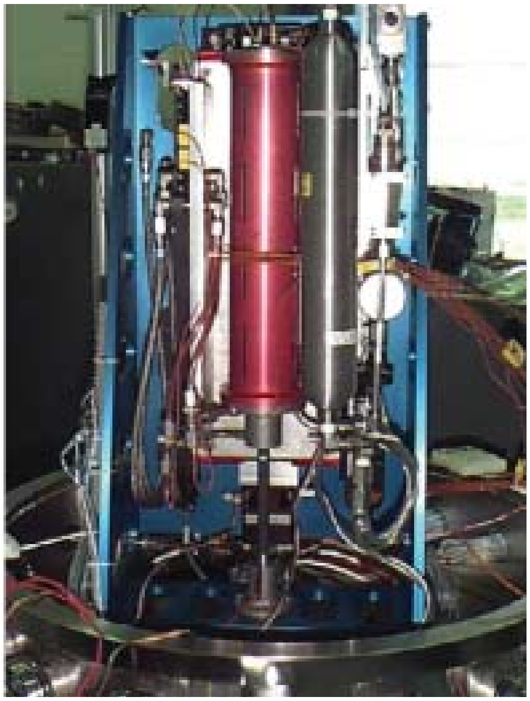
Research and Technology Development Targets (2009–2016):

- Reduce life-support system mass by a factor of three by 2010, with continuing reductions to 2016
- Perform on-orbit validation of critical life-support technologies or relevant components to certify them as candidate technologies for missions beyond LEO
- Develop and test advanced EVA components and systems for operation in partial gravity
- Conduct integrated testing of subsystem components (including humans)
- Integrate physical-chemical and bioregenerative life-support technologies, including processing crew waste, recovering nutrients, recycling air and water, and providing fresh food

4b.—What new reduced-gravity engineering systems and advanced materials are required to enable efficient and safe deep space travel?

Research Focus: Research for Engineering Solutions

Future space missions need improvement in space power and propulsion, radiation protection, and production of consumables from in situ resources. Understanding fluid and transport phenomena in a microgravity environment enables designers to improve power and propulsion systems required for deep space human exploration. Incorporation of multiphase flow systems improves thermal, mass, and size efficiencies in power subsystems such as radiators, boilers, and condensers. Efficient management of propellant inventory, precise control of liquid-vapor interface, minimum venting, and knowledge of heat transfer, wetting, and contact line behavior minimizes propellant mass for chemical and nuclear propulsion systems. A potential improvement to our program uses free-flying platforms for fundamental research as well as technology studies on cryogenic fluids and propellants at varying levels of reduced gravity.

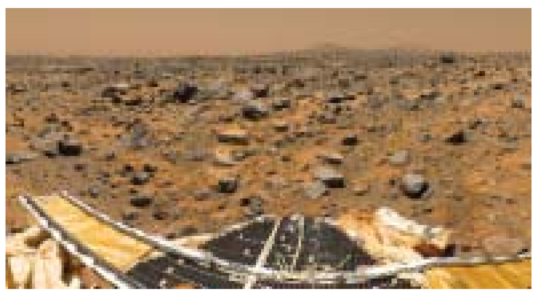


Reduced-gravity materials processing and rapid prototyping approaches will be developed and tested aboard the ISS to provide the capability for spare parts and subsystem component fabrication during potential future long-term space travel beyond LEO.

Mitigating the adverse effects of space radiation on humans requires detailed modeling of atomic- and nuclear-level interactions of radiation with relevant structural materials. New tools are needed to evaluate the development of materials for enhanced shielding. This effort complements the human adaptation research for understanding the biological effects from space radiation exposure. All contribute to developing countermeasures and protecting the crew from the radiation hazards of space flight. The focus of the research is to characterize the radiation environment as it applies to humans and develop tools for measuring the effectiveness of radiation shielding. The NSRL at Brookhaven National Laboratory is gathering experimental data on the effects of exposure of high-energy particles on materials.

The ISS is necessary to complete space-based experiments aimed at advanced in-space (i.e., not ground-based) manufacturing concepts using computer-based design and onboard materials. This research will lead to significant reductions of launch mass requirements and can be expanded to in situ utilization requiring more extensive fabrication activities. The systems to produce critical consumables (e.g., oxygen) from in situ resources must be prototyped and demonstrated in environments like those on the Moon and Mars. For example, on the Moon a fluidized bed reactor can produce oxygen, and on Mars oxygen can be produced from carbon dioxide using the reverse water-gas shift reactor. The development of these systems contributes to a safe haven for humans by providing oxygen and consumables.

In its report *Safe on Mars*, the NRC recommended precursor measurements necessary to support human operations on the Martian surface. The deployment of instruments to make these measurements is being proposed in collaboration with the Space Science Enterprise. The deployed instruments will characterize environmental hazards, determine the mechanical and adhesive properties of soil and dust, and measure the surface radiation environment.



View of the Mars terrain in the vicinity of the Sojourner Mars Lander mobile robot. Additional precursor measurements will be needed to fully understand the environmental hazards of Mars.

Research and Technology Development Targets (2004–2008):

- Improve design databases and proof-of-concept systems for phase change and two-phase flow heat transfer systems for phase separation and fluid handling devices in reduced gravity

- Demonstrate predictive models of two-phase flow and phase change heat transfer in reduced gravity

- Develop proof-of-concept systems to enable production of consumables (e.g., oxygen, fuel, water) from in situ resources

- Conduct proof-of-concept technology research for in-space fabrication of parts and subsystems

- Complete acquisition of reference data and develop theoretical models to characterize the atomic and nuclear interactions between radiation and spacecraft materials and the energies and components of radiation as a function of material type and thickness

- Develop tools to predict the radiation levels resulting from various shielding materials, such as hydrogen composites

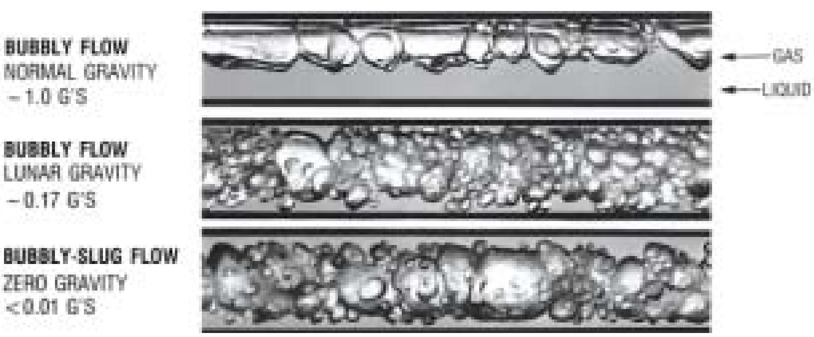
Research and Technology Development Targets (2009–2016):

- Verify and validate predictive models of systems to enable production of consumables critical for survival using in situ resources

- Verify predictive models of two-phase flow and phase change heat transfer in reduced gravity

- Integrate in-space fabrication into new spacecraft and mission design

- Conduct a radiation survey of likely destinations for extraterrestrial missions in order to develop appropriate in situ radiation-shielding strategies



The flow of gas-liquid mixtures, such as steam and water, is strongly affected by gravity. Here air-water mixtures are shown at the same flow rates, under different gravity levels. Designing devices that use steam or other gas-liquid combinations in space will require new engineering models.

- Complete development of a suite of highly effective shielding materials

- Execute free-flyer experiments in cryogenic fluids and propellant management at varying reduced-gravity levels

- Execute select environmental measurements on Mars surface in collaboration with the Space Science Enterprise

Cosmonaut Nikolai M. Budarin, Expedition Six Flight Engineer, uses a computer in a sleep station in the Zvezda Service Module on the ISS.

4c.—How can we enable optimum human performance and productivity during extended isolation from Earth?

Research Focus: Space Human Factors Engineering

During long-duration missions, humans live and work in remote confined environments with long communication times requiring autonomous systems. Advances in human factors engineering are needed to enable crews in habitable environments far from Earth to be self-supporting, autonomous, and productive. There are six organizing elements that present unique challenges:

Habitability.—Human performance, health, safety, and comfort during wake and sleep time in long-duration space habitats and Earth analogs depend on the design of environments matched to each expected activity. Acceptable activity-dependent performance ranges must be defined for environmental variables (e.g., spatial, thermal, noise, lighting, and vibration).

Physical Modeling and Design (e.g., anthropometry, biomechanics, work physiology).—Human physical performance in microgravity depends on gravity levels, transitions between those levels, protective clothing, and physiological adaptations. Tasks and equipment must be designed to accommodate these factors.

Decision Support, Information, and Control Systems.—Current knowledge limits implementation of efficient human-centered, autonomous systems. Human-centered design tools are needed to aid in the design of safe systems that enhance productivity and reduce risk.

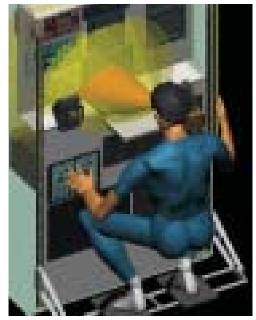
Selection, Training, and Operational Readiness.—The crew selection process must ensure that needed aptitudes, skills, and knowledge are available. The balance of skill- and task-based training must be determined to provide the greatest probability of mission success.

Multi-Agent Teams and Time Management.—Long-duration missions depend on collaborations among human, hardware, and software components. Performance models need to be developed and validated to address human factors issues such as communications, decisionmaking, mission dynamics, human-robotic interactions, and work/rest scheduling.

Integrated Human-Systems Engineering.—Human-centered design for habitat, optimal performance, interfaces, procedures, decision support, information management and control, and multi-agent teams requires the incorporation of a common systems engineering approach to the development phase. Effective human-centered design tools must support field observations and task analyses that clearly specify the requirements for human-systems interaction. These requirements and task definitions will be incorporated into computational models of sensory, motor, and cognitive performance to predict human behavior in operational scenarios.

Research and Technology Development Targets (2004–2008):

- Define requirements for habitats that optimize psychosocial, circadian rhythms, and behavioral adaptations to microgravity
- Develop predictive habitability design tools for a range of mission profiles
- Develop and validate human physical performance models based on anthropometry, strength, and endurance measurements for a variety of gravity environments that includes realistic motions and a physics-based modeling approach
- Develop tools for information interfaces and human-automation design that enhance decisionmaking, medical informatics, telemedicine, problem solving, and system control
- Develop communications and network access systems to enable decisionmaking, support problem solving, and improve communications
- Develop selection, screening, and training methods that provide the required aptitudes, skills, and knowledge for defined mission operations
- Develop analytical methods to model time management and multi-agent team performance
- Conduct research and develop an architectural framework of models and processes for human-centered integration



Computer-generated models help human factors researchers address ways that crewmembers can interact effectively with their surroundings. This model simulates a crewmember at a station research rack and factors in variables such as restraints, human reach, and vision.

Astronaut Nancy J. Currie, wearing an advanced concept space suit, participates in a test with the Robonaut at the Johnson Space Center to evaluate human-robotic operations. The Robonaut was used in this demonstration to assemble an aluminum truss structure.

Research and Technology Development Targets (2009–2016):

- Validate requirements for habitat designs for multiple missions
- Develop and assess tools on the ISS to optimize human performance
- Validate human performance optimization tools for space travel that are comparable or better than Earth-based work environments
- Extend model-based design to complex decision support, information management, and control tasks
- Determine optimum strategies for training before and during flight, to include reconfigurable onboard training capability
- Identify and evaluate space-human factors engineering technologies that have applications beyond the space program
- Develop approaches to enhance human-robotic operations

Space human factors are integral to the decision-making process for vehicle design, mission operations requirements definition, and crew performance plans. The evaluation of deliverables, whether they are ground-based or in-flight tools, mission operation guidelines, or special performance-sustaining equipment, must occur in time to be useful for critical milestones.

4d.—What automated sensing and control systems must we create to ensure that the crew is living in a safe and healthy environment?

Research Focus: Advanced Environmental Monitoring and Control

The spacecraft, crews, and habitats are susceptible to contaminants because the environments in which the crews live and work for prolonged periods are closed (i.e., air and water are recycled). This research strategy provides critical steps to monitor and control hazardous sources in spacecraft environments and habitats with advanced, integrated sensors and control systems. These systems monitor and control all potentially adverse conditions that may affect the physical, chemical, and biological environment of the crew areas. For example, detection of particular trace gases may indicate a need to increase the operation of life-support air-processing equipment. Other examples include fire detection and suppression, radiation detection and protection, and microbial and chemical hazards detection from all sources including humans.

The Trace Gas Analyzer, designed to check for ammonia leaks outside the ISS and for hydrazine on astronaut space suits or within station airlocks, is a marvel of miniaturization. The entire instrument is about the size of a shoebox and can fit on the astronaut's chestpack for environmental monitoring during extravehicular activities.

The research strategy for advanced monitoring and control systems involves six steps:

1) Determine and prioritize specific requirements

2) Identify technologies, whether current, in development, or completely new

3) Develop technologies as required

4) Demonstrate developed technologies

5) Integrate component technologies into systems

6) Apply system technologies

The emphasis of the research strategy is directed toward technology development addressing NASA-specific needs not being addressed elsewhere. It is important to leverage concurrent efforts in biomolecular technologies and microelectronics in both intramural and extramural communities, including U.S. industry. Collaborations among medical and flight operation organizations result in improvements in both monitoring and control aspects.

A critical part of the research strategy is establishing the accuracy and reliability of candidate sensors using nominal and off-nominal testing in high-fidelity simulators and other analog environments. These include: research labs, the ISS glovebox and/or rack, free-flyers, and integrated ground testing facilities. The research conducted in these environments is key to establishing the acceptable levels of contaminants that are safe for humans without causing potentially deleterious effects.

Research and Technology Development Targets (2004–2008):

- Complete water Spacecraft Maximum Allowable Concentrations (SMACs) and 80 percent of microbiological SMACs through collaboration with NASA's operational and biomedical communities
- Determine and prioritize monitoring and control research and development requirements through collaboration with advanced life-support and space human factors communities
- Develop sensors to monitor at least 90 percent of existing SMACs and to indicate fire and other potentially hazardous events
- Conduct research to reduce logistics, maintenance, and crew time requirements of sensors
- Validate sensor technologies in relevant environments
- Analyze sensor capability aboard ISS for crew safety, application to habitat monitoring, and improved medical informatics and telemedicine
- Develop methods to quantify material flammability and fire signatures in reduced gravity
- Evaluate fire-detection and -suppression techniques in space experiments
- Test control system designs that provide efficient, robust, and safe operations

Research and Technology Development Targets (2009–2016):

- Complete sensor development research for monitoring all SMACs for long-duration missions
- Integrate and validate automated sensors and control systems
- Design automated monitoring and control systems for operational flight use
- Validate best practices for fire response and recovery in reduced-gravity environments including advanced simulations for crew training
- Determine future monitoring and control requirements for extended human space exploration
- Develop miniaturized, real-time, efficient sensors for air and water contamination

Astronaut Donald R. Pettit is pictured on the ISS during the scheduled potable water sampling and on-orbit chemical/microbial analysis of the environment control and life-support system.

Earth Applications for Organizing Question 4

Enabling the crew to live and work productively in safe and habitable environments far from Earth has many applications for terrestrial settings. Each facet—from productive workers to safe work environments to energy efficiency to clean environments—applies both to space and Earth locations.

- Advanced life-support technologies for enabling autonomous human support subsystems are applicable to biological waste-processing systems in remote environments and development of clean water systems.

- Advanced technologies for onsite waste sterilization procedures could be used in health care facilities and hospitals.

- Energy efficiency and sustainability from integrated life-support systems can provide savings to residences and commercial buildings.

- Advances in plant growth research (e.g., renewable food sources) for space exploration missions aid crop improvements on Earth.

- High-efficiency energy exchange systems are relevant to current and future military and civilian applications.

- Understanding liquid-vapor separation mechanisms and wetting and contact-angle phenomena is applicable to industrial processes in the chemical, pharmaceutical, and oil-recovery industries.

- Understanding high-energy particle interaction with materials at the molecular and atomic levels impacts the nuclear power industry and provides insight into submicron processes.

- Automated dust and soil analysis instrumentation developed for Mars and other technologies for mineral extraction and gas separation is potentially applicable to similar Earth-based capabilities.

- Evaluation and design of self-contained, remote, and hazardous environments contributes valuable information with respect to human reaction and interaction in isolation and confined environments.

- Human factors research provides advancement for process control, teleoperations, and robotic systems development.

- Human performance modeling applies to the medical community's enhanced rehabilitation and therapeutic practices.

- Research in habitat development provides advances in emergency habitat and shelter deployment for a wide range of purposes on Earth (e.g., disaster, war refugee relief, and temporary emergency safe havens for rescue crews).

This new electronic nose (E-Nose) monitors the air that astronauts breathe. The E-Nose may one day aid in detecting fires, smelling chemical spills, and uncovering diseases.

Education and Public Outreach Highlights: Tools for Exploring, Tools for Learning

What new tools are needed to move humans farther along the path of exploration than they have ever ventured before? What new tools will propel the world's economy and enrich the lives of future generations? How do we utilize our existing resources in new ways? The discovery of these tools rests solidly with the students of today. Where can they learn the critical skills and ways of thinking necessary to invent, engineer, and apply these tools for exploration and enrichment?

The DIME competition enables student experimentation in physics and promotes skills in engineering and mathematics.

The Enterprise has a vested interest in encouraging the future workforce to be prepared to do just this. The Enterprise designs programs that challenge students to find creative solutions to problems and that provide hands-on opportunities. Students design and build an experiment, analyze data, and learn the effects of different gravity fields on everything from combustion to plants to fluids to advanced materials to human physiology. These experiments involve technologies needed to develop tools for future explorers.

Since 2000, high school students have proposed and conducted experiments using NASA's 24-meter Drop Tower at the Glenn Research Center in a program called DIME—Dropping In a Microgravity Environment. In the 2.2 seconds it takes an experiment to drop from the top of the tower to the ground, scientific data is collected without gravity's influence. Experiments are in a state of free-fall, or microgravity, just like experiments conducted inside an orbiting spacecraft, such as the ISS.

During the 2002/2003 competition, the selected student teams developed their experiments, worked with a scientist mentor, and learned skills of cooperation, creativity, engineering, communication, and research. The effort culminated in students attending "DIME Drop Days" at Glenn Research Center in April.

Another NASA educational program, Space Agriculture in the Classroom, sows seeds of interest in space farming and application of bioengineering concepts. Providing the ISS with enough food, oxygen, and water for each six-month stay is challenging. Supplying crews for extended missions to distant destinations will require a leap in advanced regenerative life-support technology.

To raise student awareness about the critical role of plants in the future of space exploration, NASA and the U.S. Department of Agriculture partnered to establish this program. This innovative collaboration expands the distribution of materials to a broader audience than either agency could reach independently. The established network currently serves 5 million students nationwide.

Space Agriculture in the Classroom participants analyze how different conditions affect plant growth and practice actual laboratory techniques.

Organizing Question 5.—How can we educate and inspire the next generation to take the journey?

What happens to the human body in space? What new things can we learn from microgravity? How does space research benefit people on Earth? These are some of the questions that educational and public audiences pose about the human experience in space. They are curious about the impact of space research on people today and in the future. Encouraging curiosity in students and educators plants seeds that if nurtured lead to questions, which inspire answers—and the educational journey begins.

The Biological and Physical Research Enterprise is committed to enabling the Agency to achieve its Mission of inspiring the next generation of explorers and goal of engaging the public in sharing the experience of exploration and discovery. The Educational Outreach Program shares the richness and diversity of space research in the fields of molecular and cellular biology, environmental chemistry, advanced technologies, fundamental physics, and engineering with educators and students. The Enterprise translates these space research topics into the subject areas most commonly used in science education.

This Enterprise is in an exceptional position to capture the interest of the next generation of explorers. Our ground-based and space flight research is conducted in some of the most unique laboratories in the world by leading scientists and engineers. Involving students in activities that complement or simulate authentic research promotes understanding of science concepts and the challenges of space flight. Communication from the Shuttle and the ISS connects the laboratory of space research to classrooms and homes around the world.

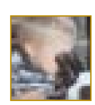
Learners of all ages are intrigued by the use of gravity as a variable, whether in flight or in ground-based research facilities. Capitalizing on this interest, the Enterprise's organizing questions bring focus to the diverse activities within this Enterprise. Discovering the answers to those questions requires creative, well-prepared future generations of explorers. Our research topics are closely aligned with the sciences taught from kindergarten through college. Innovative, well-defined educational products, events, and activities provide direct links between the people of the Enterprise, the science of space research, and learners of all ages. These authentic linkages build the pathway for educating and inspiring the next generation to take the journey.

Enterprise research and laboratory tools capture the interest of learners of all ages.

The Spaceflight and Life Sciences Training Program divides a student's time between lectures and hands-on research. This student prepares media for a microbiology experiment.

Guiding Principles

The Biological and Physical Research Enterprise Educational Outreach Program is dedicated to communicating the Enterprise's unique space research in order to inspire achievement of academic excellence; to influence the choice of science, technology, engineering, and mathematics careers; and to increase the scientific literacy of our Nation's citizenry. Reflecting the Agency's commitment to education, the Enterprise's approach aligns with NASA's Vision and Mission and the Education Enterprise's priorities and criteria for exemplary programs. We provide leadership and set benchmarks for bringing space research curriculum to our Nation's educators, students, and public.



Visual and hands-on demonstrations, coupled with personal communications with Enterprise staff and scientists, create an inspiring environment for learning.

An educational priority is to enable students to learn with understanding. Understanding science involves making linkages with other people, authentic science investigations, actual research tools and facilities, and involvement in science applications. The guiding principles of the Enterprise Educational Outreach Program assure bringing real-time exchanges with our scientific community, cutting-edge research information, and relevant educational materials to learners. The following list describes our guiding principles:

Authentic.—Our activities and products are based on current space research, tools, and technologies. Whenever feasible, activities are complemented with schematics for cost-effective, ease-of-construction educational hardware that simulates research tools.

Relevant.—The Enterprise brings relevancy to learning by engaging students in space research activities that apply standards-based science concepts.

Linked.—The Enterprise is committed to providing interactions between educators, students, researchers, science, data, and facilities.

Priorities

We have identified four priorities that relate to our primary audiences—students, educators, underrepresented and nontraditional groups, and the higher education community. The priorities are the following:

- Increase reach and interactivity of student opportunities
- Enable educators to enhance science, technology, engineering, and mathematics instruction with space research concepts
- Increase our reach to nontraditional and underrepresented students and educators
- Review, improve, and strengthen Enterprise higher education programs

These priorities define the opportunities that are offered to the primary audiences. To reach as many learners as possible, the Enterprise uses innovative techniques such as multimedia packages and outlets of popular culture, as well as traditional educator workshops and student activities.

Of utmost importance to the Enterprise is that we present the results of our research in a manner that is most beneficial to our audiences. Within these two broad groups, we focus on the higher education community as well as those groups that have been traditionally underrepresented in these fields, such as minorities and nontraditional audiences. In reaching out to such a diverse audience, it is necessary that all products and activities be developed with the guidance of experts in the field of education, including teachers and students. The products are pilot-tested to assure that they convey the research effectively and are in accordance with national standards.

Engage students.—Science is an academic discipline that effectively transcends boundaries and leads to experiential lessons known as "hands-on, minds-on" activities. Studies of people, materials, and processes in the environments of space transport students beyond the content of the textbook or lecture. The hands-on, minds-on science focus of the Enterprise activities and discussions makes connections between standards-based science concepts and relevant, real-world applications. Space research activities are designed to nurture curiosity, generate knowledge, bridge student diversities, and inspire the expression of science concepts. The Enterprise enlists a variety of methods to engage students in research-based activities that are applicable to a variety of learning environments and that increase the numbers of students reached.

Empower educators.—Both research and experience tell us that an investment in the classroom teacher is the most significant investment that can be made in improving student learning and achievement. Our strategy includes professional development opportunities that engage educators in examining research that requires creative problem solving and use of the scientific method. Educators relate their experiences to standards-based curriculum and the needs of the students with whom they work. The Enterprise focuses its professional development for educators on familiarizing them with science concepts and space research as an enhancement to classroom instruction. We use the fascination of space to encourage educators to pursue relevant, inquiry-based science activities in the classroom. Our approach involves educators at various stages of their careers through preservice training, inservice training, and continuing education credits.

Engage nontraditional and underrepresented audiences.—The Enterprise increases the reach and scope of opportunities and products to those who have traditionally been underserved and underrepresented in the sciences. This includes, but is not limited to, minorities, women, learners in urban settings and rural communities, home schoolers, and learners with disabilities. The thrust is to create mechanisms that ensure all learners have increased opportunities to excel in science, technology, engineering, and mathematics. To this end, we continue to work with minority universities through our participation in the Agency's existing programs. The Enterprise also conducts community outreach activities in strategically selected areas of the country.

The unique properties of a metallic glass, created for advanced spacecraft technology applications, are presented in a fun, visual, and student-friendly manner.

Space flight research simulations introduce students to science " . . . as only NASA can." In a prelaunch-type activity, this student loads a piece of "flight hardware" with a protein solution.

Involve higher education.—Today's students are tomorrow's scientists and engineers working to safely extend human space flight beyond low-Earth orbit. It is the responsibility of the Enterprise to provide these students with the exciting science involved in human space flight and the unique opportunities that only NASA can provide. NASA has resources that can be leveraged to reach more undergraduates, graduate students, and post-doctoral fellows. The Enterprise laboratories and facilities on Earth such as the drop towers, low-gravity aircraft, and centrifuges provide unique settings for research. The focus is to reach students in higher education in ways that increase their knowledge base and their familiarity with NASA research content, thus better preparing them to join our workforce. As part of our strategy, we develop internships and mentor programs that increase their capacity to be competitive with research proposals. The Enterprise develops undergraduate content and curriculum supplements for inclusion in college-level science, technology, engineering, and mathematics courses.

Charting Future Endeavors

The Enterprise is committed to making education an integral part of all of our space research projects. The commitment includes providing space research experiences to educational audiences through direct links with the Enterprise scientists, engineers, facilities, educational material, and activities. In doing so, we seek advice in planning, development, implementation, and assessment of our educational outreach activities from professional education associations and organizations that further a similar educational objective. Also, a series of evaluation steps and identified metrics provide a check-and-balance mechanism enabling both a formative and summative assessment. We will expand our reach into new areas, increase the scope of our products, and maximize partnerships.

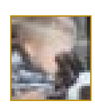
In summary, we will:

- Provide opportunities to do authentic space research in immersive environments

College students integrate science and engineering in preparation for conducting experiments aboard the KC-135.

- Use multiple techniques to reach students with varied learning styles
- Encourage lifelong learning by making space research information available to audiences of all ages through varied media and outreach events
- Increase the availability of Enterprise programs and activities to all students through the use of e-Education and partnerships
- Establish networks and partnerships with organizations that are inclusive of underrepresented educators and knowledgeable about reaching these populations
- Provide sustained professional development to preservice and practicing educators
- Correlate space research materials to national standards
- Maximize outcomes through participation in NASA education strategic initiatives
- Contribute to building the pipeline of tomorrow's scientists and engineers by supporting laboratory experiences that enable young researchers to work side-by-side with NASA researchers

The "Science in a Box" full-scale model of the Middeck Glovebox allows both children and adults to discover the challenges of working in space.



Education and Public Outreach Highlights: Ripples in the Cosmic Ocean

Each educational outreach activity is a drop in the cosmic ocean, but these drops of energy, knowledge, and curiosity create ripples. The ripples spread and swell, becoming powerful waves of energy to inspire the next generation to take the journey.

NASA's Kids Science and News Network promotes science dialogue between students. This newscaster will present research in a way that encourages his peers to "tune in" to science.

How can NASA ensure these currents are strong enough to inspire and propel the next generation to sail the cosmic ocean? NASA must reach a broad audience, creating billions of drops in the ocean. To accomplish this, the Biological and Physical Research Enterprise uses multiple mediums that appeal to mass audiences and incorporate popular culture into its outreach efforts. In 2003, the Enterprise helped produce a NASA CONNECT™ television episode that aired on the Public Broadcasting System with the potential to reach 175,000 educators representing 6.8 million students in 50 states.

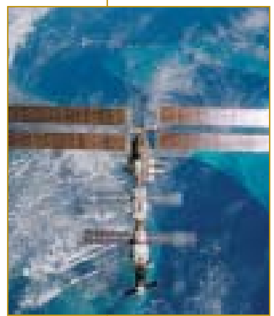
The program, "Measurement, Ratios, and Graphing: Who Added the 'Micro' to Gravity," was awarded a 2003 Emmy® Award in the children/youth program category. Through this program, students learn about microgravity and its effects on chemistry. They are introduced to combustion science and the importance of fire safety on the ISS. NASA engineers and scientists demonstrate measurement, ratios, and graphing to analyze data. Students conduct a hands-on activity and an Internet-based activity to reinforce the program's instructional objectives and establish a connection between the NASA research featured in the program and the mathematics, science, and technology principles presented by the teacher.

The Enterprise reaches another 15 million students in 5th grade through the Kids Science News Network—a series of 60-second video newsbreaks in both English and Spanish focusing on NASA and related math, science, and technology concepts.

Students' curiosities are awakened. They are ready to learn and are devoted to NASA's Mission. The Enterprise provides them with a pipeline for persevering and realizing their dreams through a variety of internships and research partnerships. The cross-disciplinary nature of the Enterprise's research offers students a variety of choices—from fundamental biology to physical sciences to bioastronautics.

Spurring the interests of students and providing career paths to enrich students' minds: these are the keys to ensuring the success of NASA's future journeys on the cosmic ocean. These are the keys to creating a strong, diverse, well-educated community that is devoted to NASA's Vision "To improve life here, to extend life to there, and to find life beyond."

At outreach events, Astronaut Roger Crouch has little trouble convincing young participants that space research is "really cool stuff!"



4 Strategy Implementation

4 Strategy Implementation

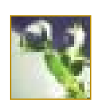
The President's Management Agenda (PMA) outlines bold new approaches to management and performance measurement for the Federal Government. In response to the PMA, NASA has developed a common set of implementing strategies to ensure that the entire Agency works safely and efficiently to achieve its Mission. The NASA Strategic Plan addresses these strategies and collectively provides a framework in which all NASA Enterprises conduct business. The Biological and Physical Research Enterprise is committed to applying these implementing strategies and highlights them in this section.

Human Resources

The Enterprise actively supports the implementation of the Agency's Strategic Human Capital Plan. This plan addresses workforce issues through an array of initiatives, tools, and legislative reforms designed to enhance management flexibility, maintain critical skills, and enhance recruitment, retention, and support of our highly diverse workforce. A vital and effective workforce is the key to our success in accomplishing the Enterprise objectives. Building on a set of competencies within the Agency, we enlist this workforce from a variety of sources including other NASA Enterprises, NASA Centers, industry, universities, other Federal agencies, and commercial and international partners.

We cannot achieve our objectives unless individuals are inspired to earn advanced degrees in science fields such as physics, biology, and chemistry, and in specialized fields such as medicine, radiation, materials, and combustion. Not only is it imperative to identify and develop needed expertise within the Enterprise, but it is also important to reach

The International Space Station flies over the Bahamas as viewed by the crew of STS-108.



The 20-G Centrifuge, used for hypergravity research at the Center for Gravitational Biology Research. The Centrifuge's cabs, located at either end of its 58-foot-diameter rotating arm and at the center of the arm, can accommodate humans or other test subjects.

out and encourage the next generation of scientists and engineers by supporting promising graduate and undergraduate students and researchers.

Unique supporting capabilities, and associated human resources talent, are required to meet the Enterprise's needs in the 21st century. These include biomedical research, advanced engineering tools, genomics, and cell sciences. The Enterprise is committed to developing the necessary human resources and supporting capabilities to enable us to reach our objectives.

International Bed Rest Facility

The Biological and Physical Research Enterprise partnered with the European Space Agency and the Centre National d'Etudes Spatiales (French Space Agency) to conduct a bed rest study at the Institute of Medicine and Physiology in Toulouse, France. The joint study will develop active intervention and rehabilitation strategies—specifically exercise and drug therapies—to prevent bone and muscle loss, and to preserve muscle strength and aerobic capacity.

Capital Resources

The Enterprise's unique objectives and technical challenges require a variety of capital resources, from communication networks to specialized test facilities. The Enterprise is committed to establishing partnerships and using existing facilities whenever possible. For example, our Bioastronautics Research Division recently developed an agreement with the French to use their bed rest facility at the Institute of Medicine and Physiology in Toulouse, rather than developing a comparable NASA facility. The Enterprise continues to seek partnerships to support facilities critical to achieving its objectives.

The Enterprise supports and builds a variety of research facilities—from ground-based laboratories, engineering test beds, and reduced-gravity facilities to space-based research assets on the International Space Station (ISS). The international partners of NASA and the Enterprise are developing multi-user facilities for research on the ISS. Table 4.1 summarizes the facilities supported by the Enterprise, with the responsible NASA Center noted.

Table 4.1

Ground-Based Facilities

Laboratory Facilities

- Space Experiments Laboratory [Glenn Research Center]
- Computational Microgravity Laboratory [Glenn Research Center]
- Center for Gravitational Biology Research (hyper-g acceleration facilities) [Ames Research Center]
- Microgravity Development Laboratory [Marshall Space Flight Center]
- Electrostatic Levitator Laboratory [Marshall Space Flight Center]
- NASA Space Radiation Laboratory [Brookhaven National Laboratory]

Test Bed Facilities

- Thermal Test Facility [Glenn Research Center]
- Bioregenerative Planetary Life-Support Systems Test Complex (BIO-PLEX) [Johnson Space Center]
- Biomass Production Chamber [Kennedy Space Center]

Low-Gravity Facilities

- 2.2-Second Drop Tower [Glenn Research Center]
- 5-Second Drop Tower [Glenn Research Center]
- Drop Tube Facility [Marshall Space Flight Center]
- KC-135 Aircraft [Johnson Space Center]

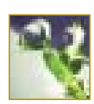
Flight Support Facilities

- ISS Payload Operations and Information Center [Marshall Space Flight Center]
- Space Life Sciences Laboratory [Kennedy Space Center]

Space-Based Facilities

International Space Station Facilities

- Materials Science Research Facility [Marshall Space Flight Center]
- Fluids and Combustion Facility [Glenn Research Center]
- Low-Temperature Microgravity Physics Facility [Jet Propulsion Laboratory]
- Express Rack [Marshall Space Flight Center]
- Human Research Facility [Johnson Space Center]
- Habitat Holding Racks with associated plant and animal habitats [Ames Research Center]
- Microgravity Science Glovebox [Marshall Space Flight Center]



The Enterprise ensures that the responsible NASA Centers develop and sustain the facilities and infrastructure needed to carry out the Enterprise's goals and objectives. Consistent with the concepts and strategies of the NASA Facilities Engineering Functional Leadership Plan and the Agency's Real Property Strategic Plan, the Enterprise will work to develop plans for the continual improvement of these recognized assets.

Information Technology

The Enterprise is committed to investment in information technology (IT) that enhances productivity and increases computer security. The Enterprise is currently designing, testing, and implementing IT that improves our ability to communicate with our stakeholders both inside and outside the Agency. We are developing a suite of tools and Web service technologies to construct applications that promote information sharing by and for all. The systems we develop are open (standards-based), extensible (easily modified for additional capability), and promote re-use of previously developed software code, allowing us to adapt to changes in technology and user requirements. We coordinate our development activities through the NASA Chief Information Officer to ensure that we integrate the use of these technologies with other parts of the Agency and the Federal Government.

Future information and data systems used for research will leverage advances in technology and improvements in price-to-performance in both hardware and software environments. The Enterprise will take advantage of continued reductions in the cost of data storage; the robustness and large bandwidth of data networks; low-cost, powerful desktop computing; advances in knowledge management; and emerging next-generation standards that will govern the Internet. These advances will strengthen the Enterprise's scientific research capabilities by providing rapid access to large volumes of information, interoperability of data systems and archives, grid computing, and data mining. The Enterprise will continue to coordinate with other Federal agencies and international partners in its focus on delivering leading-edge IT solutions.

Competitive Sourcing

Competitive sourcing, a Governmentwide initiative driven by the PMA, is fully supported by the Enterprise. Under this initiative, each Federal agency is required to review its civil service positions and determine which positions are inherently governmental and which can be considered for privatization. Competitive sourcing is not necessarily outsourcing, but competing, comparing, and/or converting eligible positions. The objective is to focus on the most effective and efficient way of accomplishing the Agency's Mission regardless of whether it is done by civil servants or contractors. An example of the Enterprise's commitment to competitive sourcing is utilization of the ISS. The ISS includes over 25 internal laboratory sites and 25 external platform sites that support U.S. research and development projects. The NASA utilization program involves extensive coordination with U.S. academic institutions, industry, and Government, as well as close liaisons with our international partners in Canada, Europe, Japan, and Russia. Under the Omnibus Appropriations Act, the Enterprise is authorized to establish a Non-Governmental Organization for research through a nonprofit ISS Research Institute to maximize productivity within fiscal constraints.

The Enterprise intends to proceed toward the establishment of the ISS Research Institute to sustain research progress while providing intellectual leadership to the diverse ISS user communities. The Institute, in partnership with NASA, will provide scientific and technical expertise in targeted areas and will have the flexibility to grow as needed to meet the needs of NASA and the ISS. Through re-competition and congressional approval, the contract could expand the scope of the Institute's overall role in ISS research management.

Partnerships

The Enterprise has developed critical relationships to assure that credible and relevant research is performed. The Enterprise strives to leverage resources, both in expertise and facilities, through a network of associations that includes other NASA Enterprises, other Government agencies, international agencies, industry, and academic institutions.

Internal to NASA

The Enterprise works very closely with other Enterprises to implement the Agency's Vision and Mission. To this end, the Enterprise and the Space Flight Enterprise (SFE) integrate research activities on the ISS. SFE is responsible for the development and operation of the ISS; the Biological and Physical Research Enterprise utilizes the ISS for research, providing the SFE with integrated requirements. The Enterprise and SFE work to ensure that astronaut crews are trained for ISS research activities and that integrated transportation plans are developed that meet operations and research needs. The Enterprise also works closely with the Advanced Systems Program in SFE to develop concepts and technologies for future human/robotic exploration.

Collaborations with the SFE and the Office of the Chief Health and Medical Officer are ongoing and documented in the 2003 *Bioastronautics Strategy*. These activities are focused on the risk-mitigation and management process for ensuring the health, safety, and performance of humans during and after space flight. The Enterprise provides research for determining the acceptable levels of risk, developing countermeasures, and addressing medical operations and flight rules.

The Enterprise's relationship with the Aerospace Technology Enterprise is established formally through membership on the Technology Executive Board (TEB). The TEB validates the objectives, requirements, and metrics for the execution of the Mission and Science Measurement (MSM) program. Through participation on the TEB, the Enterprise acts as a customer to the MSM program, providing technology requirements for accommodation. This cooperative arrangement for technology development planning across the two Enterprises makes efficient use of limited resources to achieve capabilities.

The Enterprise works with the Space Science Enterprise in the areas of astrobiology and Mars initiatives. The point of intersection between the research targets of the Astrobiology Program and the Enterprise's Fundamental Space Biology Division allows for collaborative activity. As a result, the Fundamental Space Biology Division provides yearly funding to the Astrobiology Institute—a consortium of 15 universities and other organizations—which leads NASA's astrobiology research effort. The Enterprise also works with the Space Science Enterprise to accommodate experiments on Mars robotic missions that are critical for potential future human exploration of Mars. This collaborative arrangement has led to the inclusion of a radiation measurement device on the Mars Odyssey mission and may lead to further investigations on future landed missions. Additional NASA Enterprise partnerships are shown in figure 4.1.

External to NASA

The Enterprise relies on research partnerships with experts outside of the Agency. The Enterprise actively seeks research partnerships both nationally and internationally. The external partnerships with other governmental agencies are listed in table 4.2.

The Ceratodon moss, shown below, flew on several Shuttle missions, including STS-87 and STS-107. The study of moss specimens in space under controlled lighting conditions allows scientists to focus on how gravity affects the direction of growth.

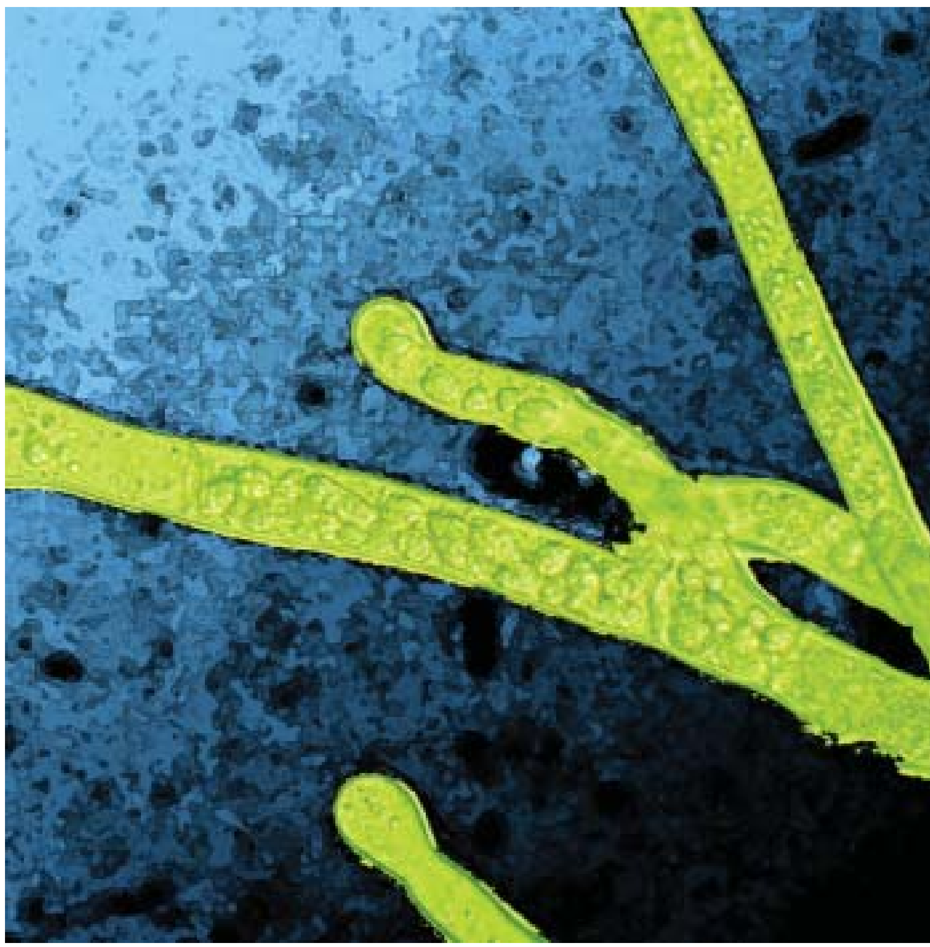


Figure 4.1

Principal Enterprise Partnerships

Space Flight Enterprise

- Functional and operational requirements for new technologies
- Spaceport launch facilities
- Integrate payloads
- Conduct experiments on the Space Shuttle and on the ISS
- Service space telescopes
- Launch robotic spacecraft on expendable launch vehicles
- Rocket propulsion testing
- Communications and data services
- Education and public outreach programs

Aerospace Technology Enterprise

- Advanced technology development and transfer
- Aerospace Technology Enterprise assets
- Systems analysis capabilities
- Technology problem-solving expertise
- Commercial technology transfer to Enterprises
- Orbital Space Plane
- Airborne sciences
- Education and public outreach programs

Space Science Enterprise

- Functional and operational requirements for new technologies
- Functional and operational requirements for launch vehicles
- Manage Deep Space Network
- Manage optical communications development
- Manage Astrobiology Program
- Provide space weather data
- Education and public outreach programs

Biological and Physical Research Enterprise

- Functional and operational requirements for new technologies
- Functional and operational requirements for launch vehicles and ISS
- Biomedical research
- Operational protocols
- Physical science design and safety standards
- Data measurement for Mars related to sustainable human presence and safety
- Education and public outreach programs

Earth Science Enterprise

- Functional and operational requirements for new technologies
- Functional and operational requirements for launch vehicles
- Study of Sun-Earth connection
- Adapt Earth system models to other planets
- Assist in improving aviation safety
- Study effects of global change on human health
- Ground network services
- Education and public outreach programs

Education Enterprise

- Guidance and integration of other Enterprises' education programs
- Linkages of NASA education programs to other Enterprises' future competencies and skill requirements
- Public outreach programs

Key

- Supports Space Flight Enterprise
- Supports Aerospace Technology Enterprise
- Supports Space Science Enterprise
- Supports Biological and Physical Research Enterprise
- Supports Earth Science Enterprise
- Supports Education Enterprise

International Partnerships

The Enterprise participates in numerous international strategic working groups with representatives from the Japan Aerospace Exploration Agency, the French Space Agency, the European Space Agency, the German Space Agency, the Italian Space Agency, the Canadian Space Agency, the National Space Agency of Ukraine, and the Russian Aviation and Space Agency. The International Microgravity Strategic Planning Group (IMSPG) coordinates the development and use of research apparatus among microgravity investigators in areas of common interest to maximize the productivity of microgravity research internationally. The International Space Life Sciences Working Group (ISLSWG) identifies mutual interests and programmatic compatibilities of the various agencies; enhances communication and unity among participating space life sciences communities around the world; and enables a more complete coordination of the international development and utilization of space flight and special ground research facilities.

Research Partnership Centers

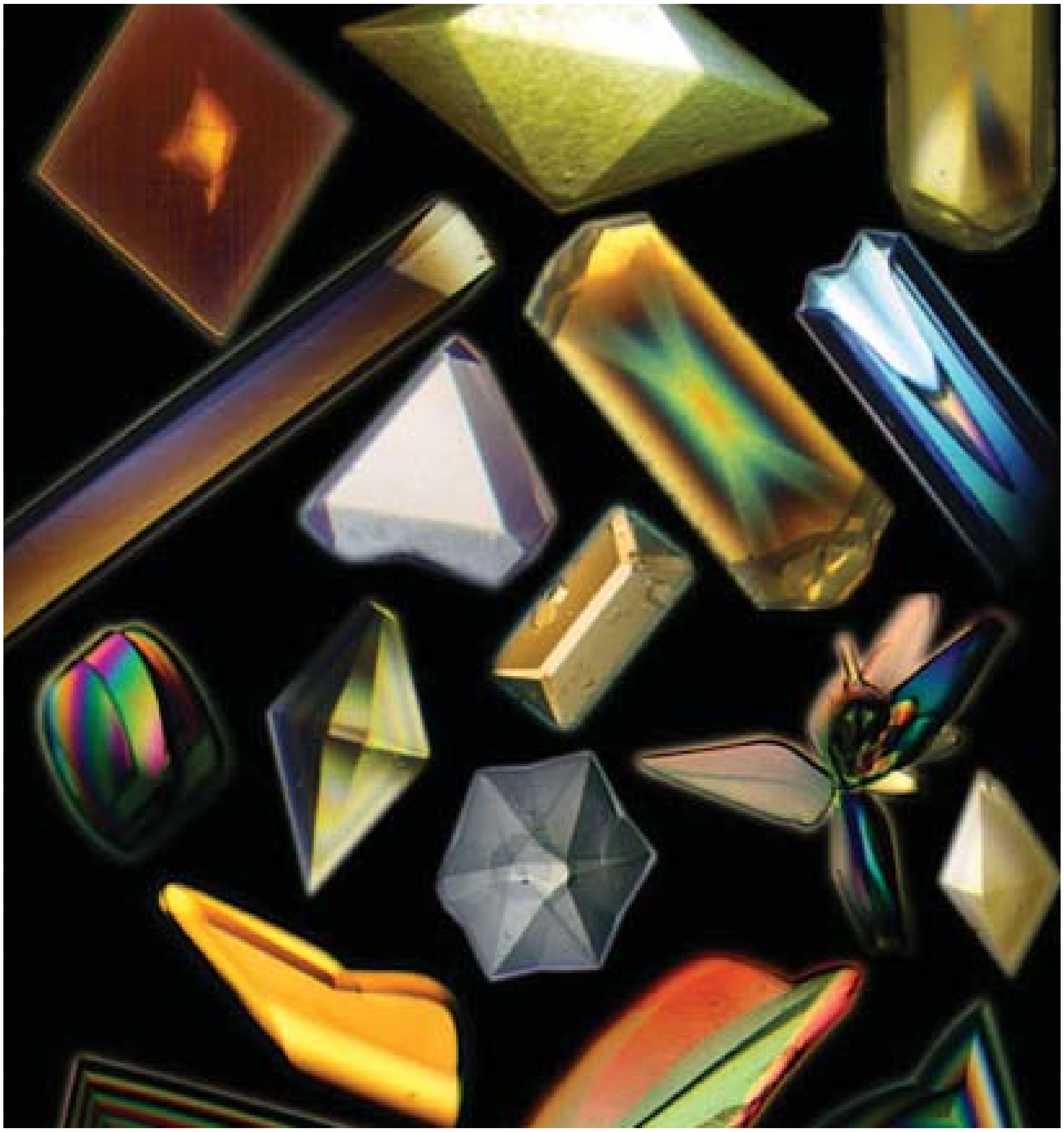
Research Partnership Centers (RPC), under the auspices of the Biological and Physical Research Enterprise's Space Product Development Division, are consortia of academic institutions, government, and industry formed to use insights gained in the space environment to develop or improve products and services on Earth. The RPC program is currently increasing its focus on advancing the Enterprise's research thrust within the key organizing questions through the consortia. At present, the 15 RPCs have more than 150 companies representing diverse fields, including agriculture, automation, biotechnology, communications, electronics, industrial processing, materials, and medical technologies.

A key element of the Space Product Development program resides in the partnerships forged between the RPCs and their industry affiliates through negotiated agreements. Though aerospace and engineering firms are substantial participants, the unique impact of the RPC program can be seen in the involvement and investment of non-aerospace organizations such as drug companies, food producers, chemical firms, hospitals and medical institutes, and refining companies. The

Table 4.2

Government Agency Partners

DOD	**Department of Defense**
■ USUHS	Uniformed Services University of the Health Sciences
■ AFRL	Air Force Research Laboratory
■ NRL	Naval Research Laboratory
■ ONR	Office of Naval Research
■ DARPA	Defense Advanced Research Projects Agency
DOE	**Department of Energy**
■ BNL	Brookhaven National Laboratory
■ OBER	Office of Biological and Environmental Research
■ ANL	Argonne National Laboratory
■ LANL	Los Alamos National Laboratory
NIH	**National Institutes of Health**
■ NCI	National Cancer Institute
■ NCRR	National Center for Research Resources
■ NHLBI	National Heart, Lung, and Blood Institute
■ NIDCD	National Institute on Deafness and Other Communication Disorders
■ NINDS	National Institute of Neurological Disorders and Stroke
■ NLM	National Library of Medicine
■ NIA	National Institute on Aging
■ NEI	National Eye Institute
■ NICHHD	National Insitute of Child Health and Human Development
Other Agencies	
■ USDA	United States Department of Agriculture
■ USGS-EDC	United States Geological Survey—EROS Data Center
■ CDC	Centers for Disease Control
■ NOAA	National Oceanic & Atmospheric Assoc.
■ NSF	National Science Foundation
■ FBI	Federal Bureau of Investigation
■ Lincoln Labs (MIT)	Lincoln Labs (Massachusetts Institute of Technology)
■ NIST	National Institute of Standards and Technology
■ FDA	Food and Drug Administration



These protein and virus crystals were photographed under polarized light (thus causing the colors) and range in size from a few hundred microns in edge length up to more than a millimeter.

RPCs bring to their partners their own research expertise along with flight hardware and the experience needed to prepare research payloads for flight: safety and flight qualification reviews, payload integration, and mission operations. Since most RPCs are university-based, they draw from the resources of the host university for undergraduate, graduate, and post-graduate student researchers, lab facilities, and specialized equipment. In return, the companies and other organizations that partner with the RPC program bring to the partnership their knowledge of the marketplace and emerging technologies. The partners invest cash and in-kind resources such as research personnel, facilities, and samples, forwarding research results into new or improved products or processes for a wide variety of markets and consumers. With this investment, the RPCs and their partners have a natural commitment to see tangible benefits emerge from space-based research.

Evaluation

The Biological and Physical Research Enterprise includes a range of programs from fundamental research and technology development to flight payload and facility development and operations. The Enterprise ensures quality research using peer review of proposals as well as advice from external committees and boards. The Enterprise's evaluation practices stem from the NASA Science Policy, formalizing NASA's commitment to funding high-quality research selected via peer review. It states that both intramural and extramural researchers will compete for funding from NASA's research programs and that the programs will be evaluated by external panels for overall quality, relevance, and performance. Panels of highly qualified scientists (for scientific content) and engineers (for technical content) review proposals submitted in response to open and broadly advertised research solicitations. Panel members are screened for competence in their respective fields as well as for apparent conflicts of interest. An Enterprise selection official makes the final selection from among the best proposals based on the results of the evaluation criteria and agreement with the Enterprise's objectives.

The Enterprise associate administrator receives advice on science priorities and implementation strategies from the Biological and Physical Research Advisory Committee (BPRAC). The BPRAC also serves as a subordinate committee to the NASA Advisory Council, which advises the NASA Administrator on Agency programs, policies, and plans. The BPRAC's advice spans research in the areas of biology, physical sciences, biomedical, advanced human support technology, and commercial research in space. The BPRAC also serves to transmit information about policies and decisions of the Enterprise to its constituent research community members.

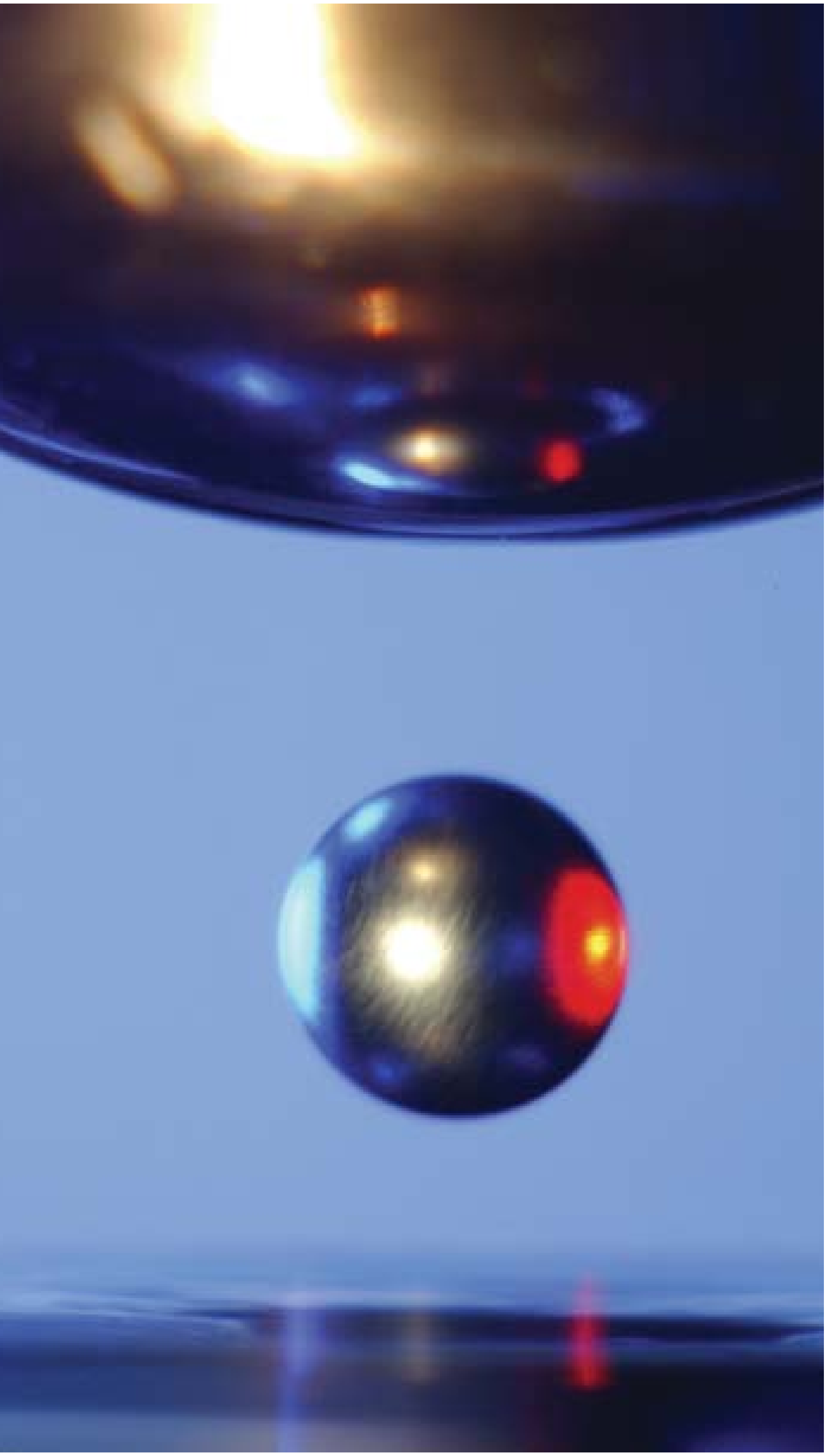
In addition to the input received from the BPRAC, the Enterprise also solicits and receives independent advice from boards and committees of the National Research Council (NRC). Unlike the BPRAC, the NRC appoints its own members and sets its own meeting agendas. The Enterprise utilizes primarily two NRC boards: the Space Studies Board and the Aeronautics and Space Engineering Board. Recent NRC reports issued for the Enterprise include *Assessment of Directions in Microgravity and Physical Sciences Research at NASA* (2003) and *Safe Passage: Astronaut Care for Exploration Missions* (2001).

Communications

The Enterprise is committed to communicating the excitement of science research and exploration to the Nation through promoting and advancing space research. Efforts to reach diverse communities, inspire a new generation of scientists and engineers, and encourage future explorers are key elements of the Biological and Physical Research Enterprise communications strategy. Space research is an evolving field of discovery, enabling and extending human exploration of space while developing new knowledge and applications to improve life on Earth.

An updated Enterprise communication strategy for public outreach activities is under development. We are strengthening our emphasis on education and public outreach in all aspects of our research programs, and we are developing new processes to support this increased outreach. Strategic investment decisions will ensure that products are developed and presented in a coherent, well-organized manner that focuses on the intended user community, including the American public, policymakers, and the media.

The Enterprise's outreach efforts focus on the public as well as the research community. Outreach increases awareness and understanding of space research and its benefits. The Enterprise has an obligation and commitment to describe to the public the return from their investment in space. To inspire the public, the Enterprise endeavors to make space research a part of everyday lives. Reaching out to the research community increases awareness of and participation in space research by scientific, engineering, and commercial investigators, with the goal of building a more cohesive space research community. Sharing work conducted on the ISS with these audiences provides access to the experience and excitement of space research. Public and user outreach promotes the dissemination of knowledge and technologies derived from space research for application in space and on Earth.

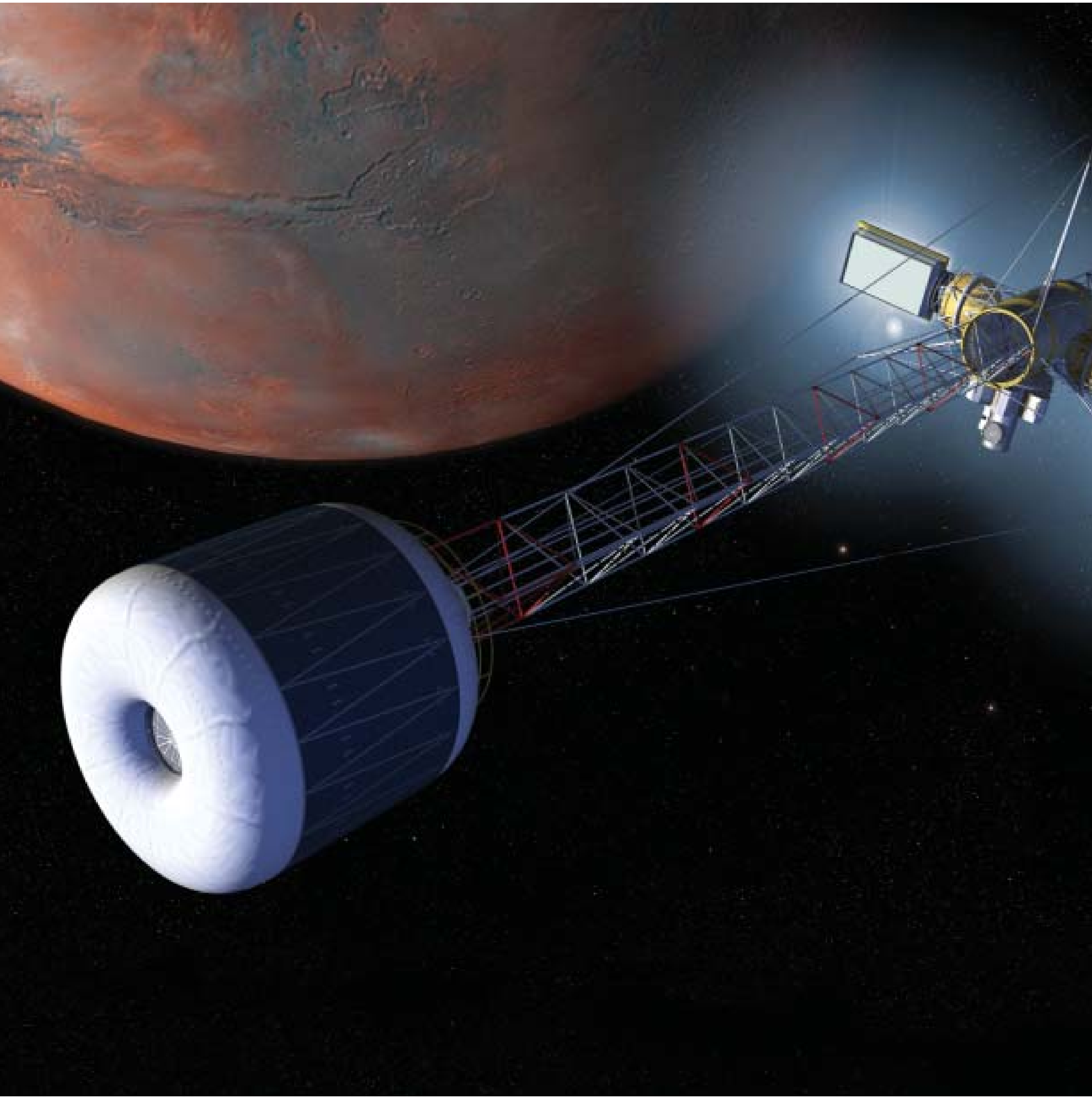


Several overarching principles are guiding the development and implementation of the Enterprise's outreach strategy, including:

- Support the NASA Mission and be consistent and integrated with NASA's Strategic Plan, the Education Enterprise's goals and objectives, and other Agency outreach priorities, such as those of NASA Public Affairs
- Maintain consistency with the "One NASA" approach by collaborating with other NASA organizations and by focusing on Enterprise-specific capabilities
- Focus on outcome goals, metrics, and evaluation
- Reach minority, underrepresented, and nontraditional audiences
- Seek partnerships and collaborations with external organizations to leverage outreach effectiveness
- Make outreach an integral element of all Enterprise research activities
- Enhance outreach to all audiences through consistent, creative media communications
- Communicate accurate information in compelling, engaging terms and methods

Using an electrostatic levitator, researchers validated a 50-year-old hypothesis explaining how liquid metals resist turning into solids. The ground-based experiment was conducted in preparation for flight on the ISS where microgravity conditions will make it possible to levitate larger samples and better characterize how metals form microstructure as they solidify.

5 Beyond the Horizon



5 Beyond the Horizon

"What was most significant about the lunar voyage was not that men set foot on the Moon but that they set eye on the Earth. To be able, from a station in outer space, to see the relationship of the planet Earth to other planets; to be able to contemplate the billions of factors in precise and beautiful combination that make human existence possible; to be able to meditate on journeying through an infinity of galaxies; to be able to dwell upon an encounter of the human brain and spirit with the universe—all this enlarges the human horizon. It also offers proof that technology is subordinate to human imagination; we can do this not just because of technology but because of our imagination."

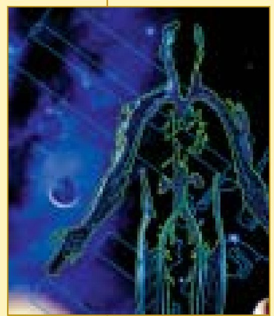
—Norman Cousins
Editor and Writer, 1915–1990

Bold imagination brought the Apollo era, the Hubble era, the International Space Station era, and a host of other NASA achievements to fruition. The next phase in space activity, with the certain consequences of enlarging the human horizon, is eminent.

Whether returning to the Moon, cruising to a libration point, or traveling to Mars—the next explorers will encounter many unforeseen challenges as well as many opportunities. The Enterprise's mission is to ensure they are physically prepared, equipped with the appropriate tools, and knowledgeable about operating in foreign environments. Looking beyond the ISS horizon also offers our Enterprise new vistas from which to perform research. Our probing questions on the fundamental nature of physics and biology can be asked from destinations other than LEO where the variables of radiation and gravity are changed. The awaiting scientific discoveries will enlarge the human horizon.

This artist's rendition depicts a human Mars transfer vehicle equipped with artificial gravity mechanisms. (courtesy of John Frassanito and Associates)

For more information regarding the work of the
Biological and Physical Research Enterprise, please visit our Web site
http://spaceresearch.nasa.gov



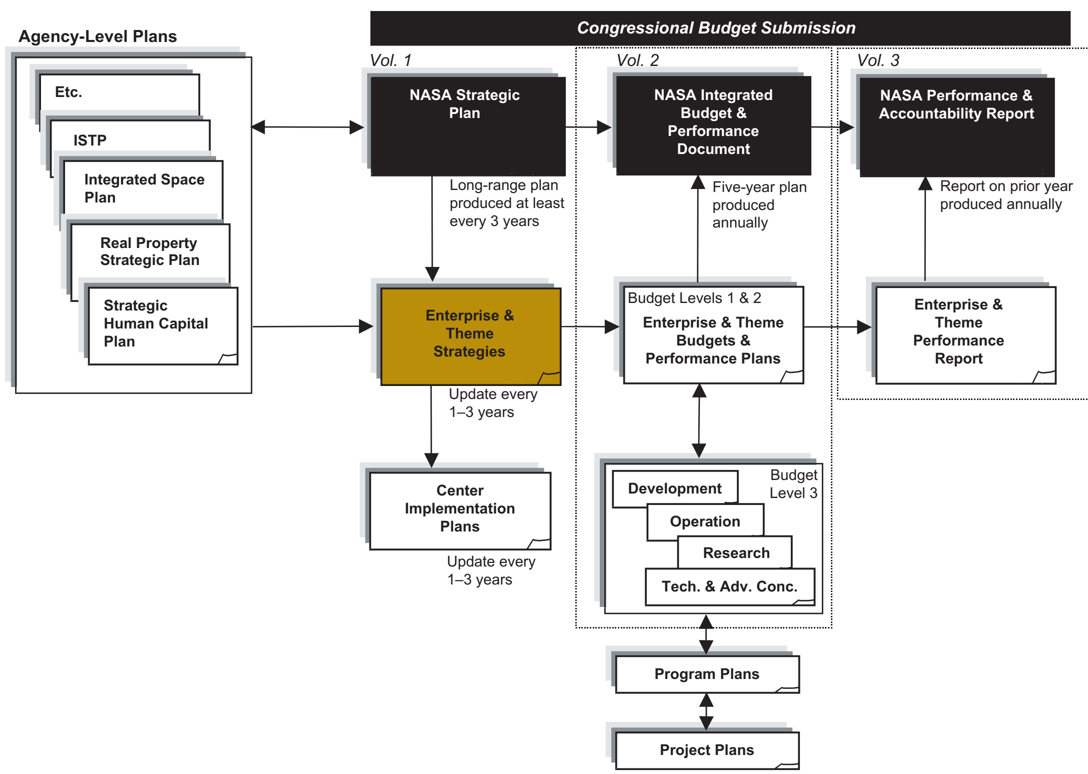
Appendices

Appendix 1

Relationship to Agency Planning

The Agency's planning process includes the development of a Strategic Plan, the annual budget, and a performance plan. The Strategic Plan is a 5-year plan, updated every 3 years, that defines the Agency's goals and objectives. The NASA Enterprises base their planning on the strategic emphasis, implementing strategies, goals, and objectives outlined in the Strategic Plan. In addition, Enterprise budget planning and performance reporting are directly traceable to the Agency-level documents.

The Enterprise Strategy communicates the results of the Agency and Enterprise planning processes to the NASA stakeholders and other audiences listed below.



Stakeholder/Audience	Enterprise Strategy Function
Executive and Legislative Branches	Communicate purpose and value of investments
NASA Employees	Achieve alignment within the Enterprise and Agency
Other NASA Enterprises	Strengthen inter-Enterprise collaboration
Science Community	Document consensus on objectives and priorities
Contractor Community	Communicate programmatic objectives and priorities
Interagency, International, and Commercial Partners	Establish basis for future collaborations
The Public	Inform and inspire

Appendix 2
Additional Information

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Appendix 3

Acronym List

AHST	Advanced Human Support Technology
BNL	Brookhaven National Laboratory
BPRAC	Biological and Physical Research Advisory Committee
CPR	cardiopulmonary resuscitation
CSC	Commercial Space Centers
CSE	Clinical Status Evaluation
DIME	Dropping in a Microgravity Environment
DOD	Department of Defense
DOE	Department of Energy
EVA	Extravehicular Activity
FASEB	Federation of American Societies for Experimental Biology
HDTV	High Definition Television
HZE	Galactic Cosmic Rays w/High Energy Nuclei
IT	Information Technology
IMSPG	International Microgravity Strategic Planning Group
ISLSWG	International Space Life Sciences Working Group
ISS	International Space Station
LEO	low-Earth orbit
MSM	Mission and Science Measurement
NEEMO	NASA's Extreme Environmental Mission Operations
NIH	National Institutes of Health
NRC	National Research Council
NSBRI	National Space Biomedical Research Institute
NSRL	NASA Space Radiation Laboratory
OBPR	Office of Biological and Physical Research
PARCS	Primary Atomic Reference Clock in Space
PMA	President's Management Agenda
PuFF	Pulmonary Function in Flight
RPC	Research Partnership Center
SFE	Space Flight Enterprise
SMAC	Spacecraft Maximum Allowable Concentration
SPE	Solar Particle Events
SQUID	Superconducting Quantum Interferometry Device
STS	Space Transportation System
TEB	Technology Executive Board
TRL	Technology Readiness Levels

Space Shuttle Columbia's Lasting Legacy

Keeping Cells in Suspense.—On the Space Shuttle Columbia's final mission, STS-107, astronauts helped scientists study how prostate cancer cells and bone cells come together. The goal was to learn how the cells interact when cancer began to spread. Columbia's astronauts used a device invented by NASA called a bioreactor. The bioreactor helps researchers turn cell cultures into functional tissue, which can be used for experiments, transplants, and drug development. Without a bioreactor, cells fall to the bottom of a petri dish and grow as a sheet one cell layer thick—thinner than a human hair. In NASA's space bioreactor, the cells stay suspended and form the kind of large samples researchers need. During the Columbia mission, the cell "assembly" grew to the size of a roll of pennies, much larger than anything researchers have seen before. The Shuttle experiment was so successful that NASA plans to fly similar, longer-term experiments on the International Space Station.

Cleaner Cars.—Space flight research is changing our understanding of how and why things burn—a phenomena scientists thought they understood thoroughly. For example, one hydrogen experiment aboard STS-107 produced the weakest flames ever created, 100 times weaker than a birthday candle. That research—improving the burning of hydrogen—could result in cleaner-burning cars in the future and other fuels in engines and furnaces. Two major corporations, Pratt and Whitney and General Electric, have already used space-flight combustion research to improve their jet engines.

Shifting Sands.—A materials science experiment (Mechanics of Granular Materials) collected data on how granular materials (e.g., sand) respond to physical stressors, yielding new knowledge that can be applied to better predict how soils react in an earthquake.

Fighting Fires.—The crew worked diligently on a commercial experiment called WaterMist, focused on the formation of flames and the use of water droplets to quench them. Results will provide an important fire-fighting tool to replace chemical fire suppressants, such as Halon, banned for use by the Montreal Protocol.

Recovered Data.—Perhaps the most extraordinary data collected from the mission were the specimens that were recovered in the debris of Columbia. Samples of moss from an experiment studying the effects of microgravity on plant growth (Development of Gravity Sensitive Plant Cells in Microgravity) were found. The moss had been preserved in a chemical fixative in orbit. It is hoped that the samples recovered will yield information about what was responsible for a unique growth pattern that had been observed in moss grown on a previous space flight. The STS-107 moss also had the same, previously unpredicted, spiral growth pattern.

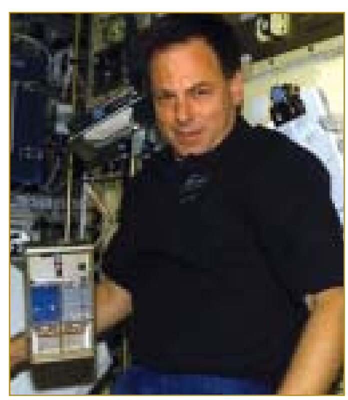
Finally, in a totally unexpected discovery, live worms (i.e., *C. elegans*, a small roundworm often used in biological research) were found after the accident. They had flown on STS-107 as part of a technology demonstration project to test a new media that could be used in future space experiments to grow the worms. Not only did the discovery of the live samples demonstrate the ability of the growth media to support and sustain the worms, the specimens are being studied to determine what other changes may have occurred as a result of their space flight.

In memory of the STS-107 crew
and their dedication to the pursuits of the
Biological and Physical Research Enterprise.









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